

The Double Galaxy Cluster Abell 2465 I. Basic Properties: Optical Imaging and Spectroscopy

Gary A. Wegner¹

¹*Department of Physics & Astronomy, Dartmouth College, 6127 Wilder Laboratory, Hanover, NH 03755, U.S.A.*

Accepted ; in original form

ABSTRACT

Optical imaging and spectroscopic observations of the $z = 0.245$ double galaxy cluster Abell 2465 are described. This object appears to be undergoing a major merger. It is a double X-ray source and is detected in the radio at 1.4 GHz. The purpose of this paper is to investigate signatures of the interaction of the two components. Redshifts were measured to determine velocity dispersions and virial radii of each component. The technique of fuzzy clustering was used to assign membership weights to the galaxies in each clump. Using redshifts of 93 cluster members within 1.4 Mpc of the subcluster centres, the virial mass of the NE component is $M_V = 4.1 \pm 0.8 \times 10^{14} M_\odot$ and $M_V = 3.8 \pm 0.8 \times 10^{14} M_\odot$ for the SW. These agree within the errors with masses from X-ray scaling relations. The projected velocity difference between the two subclusters is $205 \pm 149 \text{ km s}^{-1}$. The anisotropy parameter, β , is found to be low for both components. Spectra of 37% of the spectroscopically observed galaxies show emission lines and are predominantly star forming in the diagnostic diagram. No strong AGN sources were found. The emission line galaxies tend to lie between the two cluster centres with more near the SW clump. The luminosity functions of the two subclusters differ. The NE component is similar to many rich clusters, while the SW component has more faint galaxies. The NE clump's light profile follows a single NFW profile with $c = 10$ while the SW is better fit with an extended outer region and a compact inner core, consistent with available X-ray data indicating that the SW clump has a cooling core. The observed differences and properties of the two components of Abell 2465 are interpreted to have been caused by a collision 2-4 Gyr ago, after which they have moved apart and are now near their apocentres, although the start of a merger remains a possibility. The number of emission line galaxies gives weight to the idea that galaxy cluster collisions trigger star formation.

Key words: galaxies: clusters: general – galaxies: clusters: individual: Abell 2465

1 INTRODUCTION

Fundamental questions of current astrophysics involve the roles of dark matter, baryonic matter, and dark energy as driven by gravity in the formation of the large-scale structure and galaxies. Double or multiple galaxy clusters can potentially provide information on the dynamics and structure formation on ($r \gtrsim 1$ Mpc) scales and interest in them has grown from both the standpoints of modelling and observation.

Although the presence of substructure in galaxy clusters has long been known, compared to single galaxy clusters, the properties of double and multiple clusters have received less attention owing to their added complexity. Interest in the observed substructure of galaxy clusters was pioneered by, e.g., Geller & Beers (1982) and studies employing the radial

infall model (Beers, Geller & Huchra 1982; Beers et al. 1991) was used for rough dynamical estimates.

With the realization of their importance, a growing number of systems have now been more fully studied dynamically, from weak lensing, and in X-rays. A partial list includes: Abell 168 (Hallman & Markevitch 2004), Abell 399/401 (Sakelliou & Ponman 2004), Abell 520 (Girardi et al. 2008), Abell 521 (Ferrari et al. 2003), Cl0024+17 (Jee et al. 2007), the “bullet cluster,” 1E0657-56 (Clowe et al. 2006), Abell 2146 (Russell et al. 2010), RXJ1347.5-1145 (Bradač et al. 2008a), A399 and A401 (Yuan et al. 2005), Abell 2163 (Maurogordato et al. 2008), Abell 85 (Tanaka et al. 2010), and Abell 901/902 (Heiderman et al. 2009). Okabe & Umetsu (2008) studied seven merging clusters using weak lensing.

Radio emission from merging clusters in the form of diffuse non-thermal radio halos or relics that arise from merger

shocks in the interactions of the colliding galaxy clusters have also been described by several groups including Slee, Roy, & Murgia (2001), Feretti (2002) who describe several objects, Bagchi et al. (2006), Abell 3376, Orrú et al. (2007), Abell 2744 and Abell 2219, Bonafede et al. (2009), Abell 2345, van Weeren et al. (2009), A2256. Skillman et al. (2010) summarize the modeling situation.

Modelling galaxy cluster mergers and collisions predict observable signatures (e.g., Roettiger et al. (1996, 1997; Ricker 1998; Tazikawa 2000; Ricker & Sarazin 2001; Ritchie & Thomas 2002; Springel & Farrar 2007; Mastropietro & Burkert 2008; Poole et al. 2008; Planelles & Quilis 2009). These simulations have mostly focused on the behavior of the baryonic and dark matter components and use a range of initial profiles and conditions and impact parameters which include both off-centre and head-on collisions. These calculations predict differing behaviors for the baryonic and dark matter components of the clusters at subsequent phases of the collisions. In a typical merger, the dark matter and the baryonic gas are elongated along the collision axis with a displacement between the baryonic and dark matter components. The gas, in addition, is shocked which results in multiple X-ray peaks and gas splashed perpendicularly to the direction of the merger. This produces non-isothermal temperature distributions and the increased ram pressure from the shocks could induce star formation in the member galaxies as well as 'sloshing' (Markevitch & Vikhlinin 2007).

Several authors have attempted to extract information from double and multiple galaxy clusters on the nature of gravity and dark matter on galactic cluster (~ 1 Mpc) distance scales and up to now this has mainly centred on analyzing the 1E0657-56 cluster. Farrar & Rosen (2006), Brownstein & Moffat (2007), Angus & McGaugh (2008), Schmidt, Vikhlinin, & Hu (2009), and De Lorenci, Faundez-Abans, & Pereira (2009) are among those who investigated whether modifications to gravity are needed to fit the available dynamical data. Springel & Farrar (2007), Pointecouteau & Silk (2005), and Hayashi & White (2006), however indicated that modifications are unnecessary. For studying the properties of dark matter, the situation is somewhat more definite. Clowe et al. (2006) used weak lensing measurements of the bullet cluster to indicate direct proof of the presence of dark matter from the offset between the X-ray gas and the lensing centres. Shan et al. (2010) have studied further offsets between dark and ordinary matter in a further 38 lensed galaxy clusters. Galaxy clusters have been employed to place limits on neutrino masses (e.g., Tremaine & Gunn 1979; Angus, Famaey, & Diaferio 2010; Natarajan & Zhao 2008) and discussed whether or not such particle masses are needed to save the modified Newtonian dynamics formula.

Even if one dismisses such claims, a considerable amount of more conventional information is obtainable from double galaxy clusters. This includes possible modifications to luminosity functions, mass profiles and velocity dispersion anisotropy measures (the β parameter) as a result of their interactions. Luminosity functions contain information on the galaxy formation history (e.g., Bingelli, Sandage & Tammann 1988) and have been studied in detail at a range of redshifts and environments, mostly for single systems (e.g., Wilson et al. 1997; De Propis et al. 2004; Blanton et al. 2003; Christlein & Zabludoff 2003; Goto et al. 2005). Generally single, and double Schechter functions (Schechter 1976), and

Gaussian functions have been used to fit the LFs. Collisions may modify these properties compared to isolated single clusters at some level, but this question about the effects of merging in double galaxy clusters, whether or not their interactions produce or lower star formation along with AGN activity, has not been answered yet. Hwang & Lee (2009) have reviewed empirical and theoretical evidence for this and conclude that observations support the importance of mergers. Haines et al. (2009) and Chung (2010) have reported evidence of enhanced star formation rates in interacting clusters including the bullet cluster.

Mergers can distort galaxy cluster mass profiles. Many investigators have compared theoretical mass profiles with observations (e.g., Biviano & Girardi 2003; Katgert, Biviano, & Mazure 2004; Pointecouteau, Arnaud, & Pratt 2005; Kubo et al. 2007; Okabe & Umetsu 2008). Although not all details of these models are agreed upon, the NFW profile (Navarro, Frenk, & White 1997) fits most observed profiles within the virial radius with a concentration parameter, c for galaxy clusters is in the range of $c = 4 - 6$ in agreement with theoretical results (e.g., Zhao et al. 2003). In addition, for a spherical system with the NFW profile, the anisotropy parameter $\beta = 1 - \sigma_\theta/\sigma_r$ (where σ_θ is the azimuthal velocity dispersion and σ_r the radial velocity dispersion), is predicted to be near 0 at the centre and to increase to about 0.3 beyond the virial radius and can provide information on the properties of the dark matter (Host 2009).

Many of the systems described in the literature are multiple and complex or minor mergers where the mass of one component is considerably larger than the other. The Abell 2465 double cluster discussed in this paper has a relatively uncomplicated substructure and shows some evidence for either a past collision or a commencing merger between the two components. The mean redshift is $z = 0.245$. ROSAT (Perlman et al. 2002), XMM (2008) data, and redshifts show two physically related X-ray sources $5.5'$ (1.2 Mpc) apart (hereafter the NE and SW clumps). As well, it is a 1.4 GHz radio source in the NVSS (Condon et al. 1998). Both the virial and X-ray masses obtained in this paper indicate that the mass ratio of the two clumps is close to 1:1. Therefore the Abell 2465 is an example of a relatively rare major merger.

This paper surveys the optical properties of Abell 2465 cluster and is organized as follows: Section 2 describes the new imaging and spectroscopy, Section 3 gives estimates from spectroscopy of virial masses and radii, values of β , and discusses available X-ray and radio data and emission line galaxies in the two subclusters found from the spectra. Section 4 describes the determination of the luminosity functions, and Section 5 compares the estimates of the light profile and the corresponding mass profile. Section 6 discusses the results in relation to a collision, and Section 7 lists the conclusions. The WMAP 5 year cosmological parameters are used throughout this paper.

2 OBSERVATIONS

Figure 1 shows the central $8'.1 \times 8'.1$ section of the i' CFHT image described below, containing both clumps of Abell 2465 (hereafter denoted SW and NE). Basic astronomical data are given in Table 1. The centres of the two clumps are separated by $5.5'$.

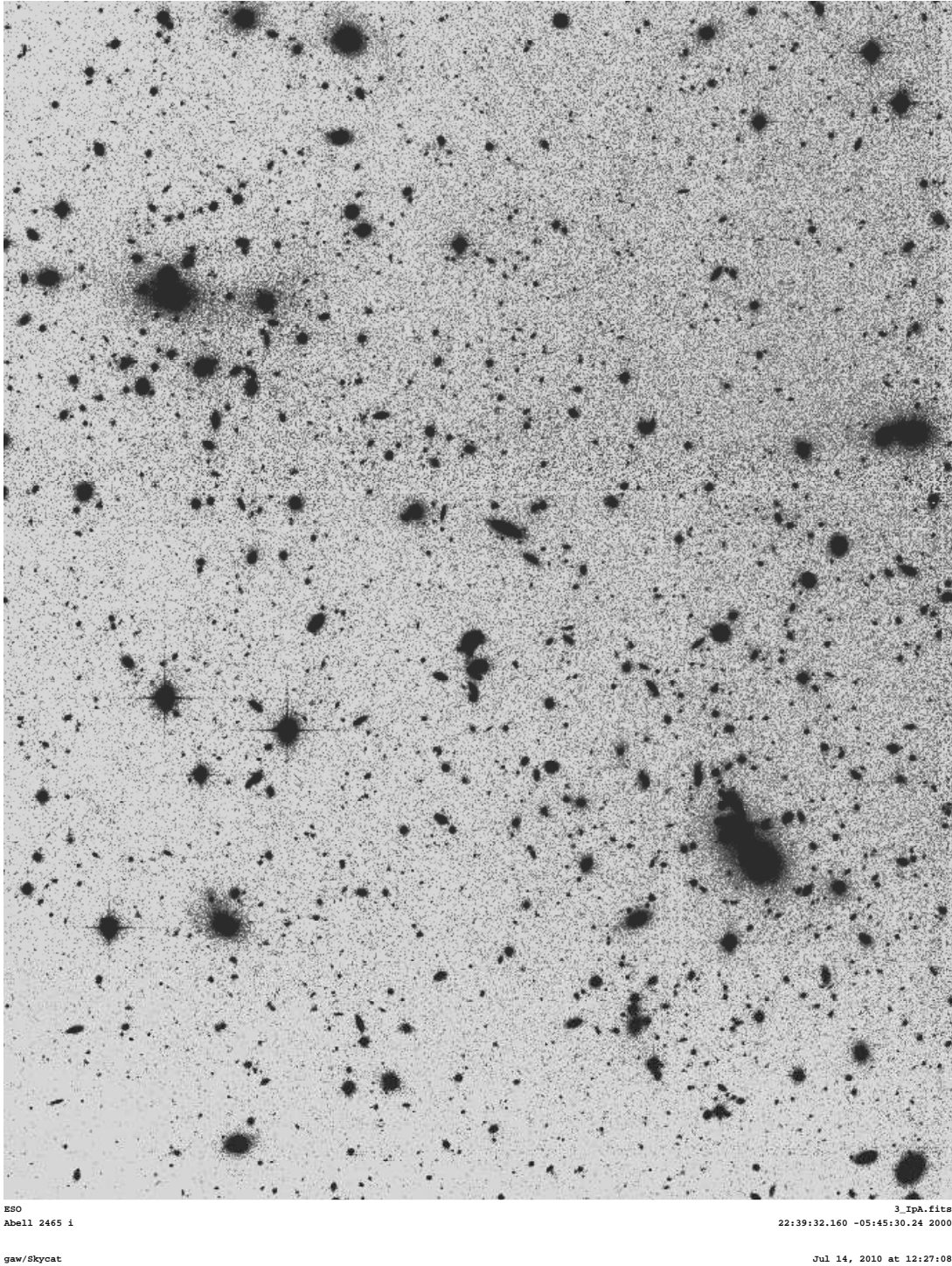


Figure 1. A portion of the combined CFHT i' Megaprime images of the centre of Abell 2465 showing the NE (upper left) and SW (lower right) clumps. The vertical edges of the picture are $8'.1$ in length. North is to the top and East is to the left. (Plot made using ESO's SkyCat, <http://archive.eso.org/cms/tools-documentation/skycat>).

2.1 Imaging Data

The main part of the imaging data used in this paper is based on two sets of r' and i' images obtained by the QSO group of the CFHT in 2009. Five dithered r' images of 300 seconds exposure each were taken 17 August at mean air-

mass 1.765 and five dithered i' images, each of 412 seconds were observed 23 August at mean airmass 1.36 using the

Megaprime instrument.¹ The ELIXER reductions of these images provided by the CFHT, which included bias subtraction and flattening, were employed and the photometric zero points and extinctions provided for the run were used, although these were checked as explained below. The sets of dithered images were combined using the MSCRED programs in IRAF². The task MSCFINDER was employed to put coordinates to the WCS scale using the USNO-b catalogue. The program MSCIMAGE was used to make one single image from the 36 individual CCD images and each of these were stacked to make a final r' and i' image with the task MSCSTACK. The resulting FWHM of stellar images in the vicinity of Abell 2465 are $0''.81$ and $0''.47$ for r' and i' respectively.

2.1.1 Photometry

The photometry of the images was measured using the SEXTRACTOR programme (Bertin & Arnouts 1996; Bertin 2009; Holwerda 2005). The single image mode was firstly used to scan the i' image, which was secured in better seeing, to locate objects, and the double image mode was secondly run for the r' image. The MAG_AUTO option and mostly default parameters recommended by Bertin (2009) for measurements of galaxies were set in the Sextractor. The colour zeropoints and extinctions provided by the ELIXER processing were employed. These were checked for the brightest galaxies using CCD images of Abell 2465 obtained under photometric conditions from the 1.3 m telescope at the MDM Observatory in Arizona with Kron-Cousins R and I filters on the nights of 1995 November 18, 19, and 21 and 2009 October 15 and 16 and calibrated using Landolt (2009) with the result that $R = r' - 0.13 \pm 0.03$ and $I = i' - 0.61 \pm 0.05$. Jordi et al. (2006) and Chionis & Gaskell (2008) give comparable values within the errors for objects in the early-type galaxy colour range.

2.1.2 Star/Galaxy Separation

The SEXTRACTOR programme provides the CLASS_STAR stellerity parameter $0 \leq s \leq 1$, whereby objects with $s \approx 1$ are stellar-like and $s \approx 0$ are galaxy-like. The s grows increasingly imprecise for faint sources due to seeing effects, so a better delineation between stars and galaxies is to employ the relation between MAG_AUTO, the Kron-like elliptical aperture magnitude, and MU_MAX, the peak surface brightness above background (Leauthaud et al. 2007; Penny et al. 2010). Figure 2 plots objects in the i' image for which $s \geq 0.8$. The stellar locus and the outlined area used to determine which objects were stars is shown. If an object lies in this region and has $s \geq 0.8$, it was classed as a star.

¹ A description of this instrument including filters and ELIXER reductions can be found on the CFHT web-page: <http://ftp.cfht.hawaii.edu/Instruments/Imaging/MegaPrime/>

² IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table 1. Basic Data for Abell 2465 used in This Paper

(1)	(2)
NE XMM α_{J2000}	22 39 39.02
NE XMM δ_{J2000}	-05 43 28.2
SW XMM α_{J2000}	22 39 24.65
SW XMM δ_{J2000}	-05 47 15.0
NE BCG α_{J2000}	22 39 40.491
NE BCG δ_{J2000}	-05 43 26.75
SW BCG α_{J2000}	22 39 24.572
SW BCG δ_{J2000}	-05 47 17.37
Mean Redshift z^1	0.2453 ± 0.0002
Luminosity Distance ²	1224 Mpc
Angular-size Distance ²	791 Mpc
Distance Modulus ²	40.44 mag.
Cosmology Corrected Scale ²	230.06 kpc arcmin ⁻¹
Galactic Extinction A_I^2	0.077 mag
K-term $K_I(z)^3$	0.15 mag

¹This paper, mean of 149 redshifts ²From NED using the WMAP 5-year parameters. The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. ³Blanton & Roweis (2007); Fukugita et al. (1995)

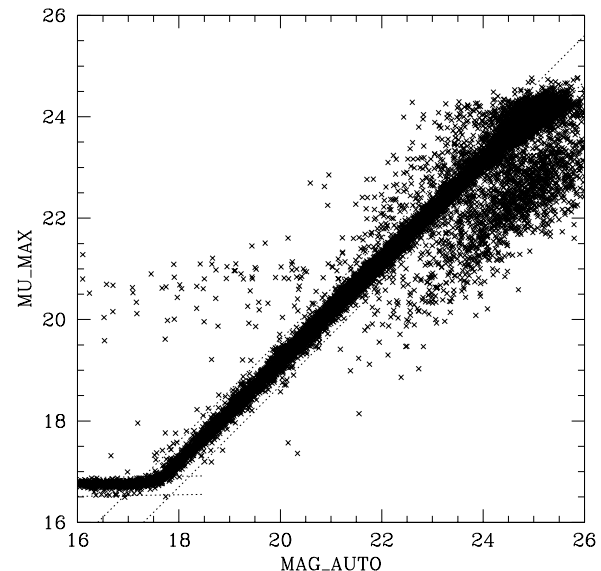


Figure 2. MU_MAX versus i' MAG_AUTO from SEXTRACTOR for stellar-like objects with $s > 0.8$ in the CFHT image. Dotted lines give the outlines of the region used to reject stars.

2.1.3 The Red Sequence

Using the objects classified as non-stellar or hence galaxies discussed above, the plot of i' against $(r' - i')$ colours centred on Abell 2465 shows a well defined red sequence. Figure-3 shows the magnitude-colour plot for the inner $18' \times 12'$ rectangle which contains the two subclusters. The red se-

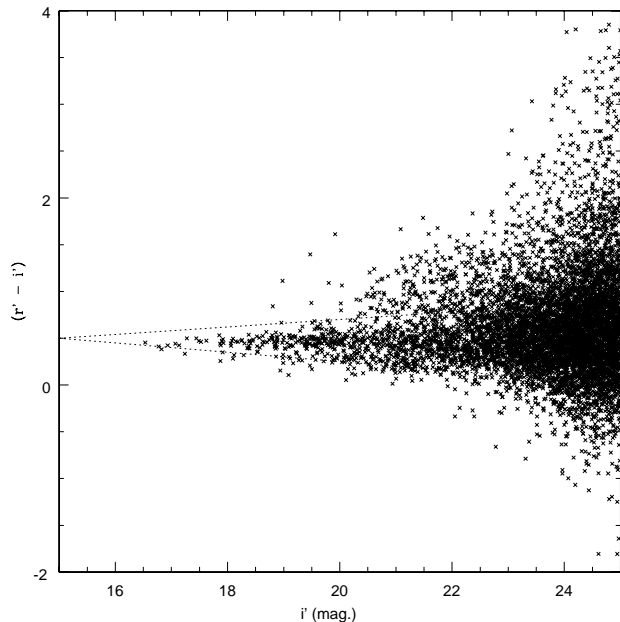


Figure 3. The red sequence for the objects classed as non-stellar in the inner $18' \times 12'$ central portion of the CFHT images. Dotted lines give the outlines of the region used to select red sequence cluster members.

quence is visible and the region used in the following is indicated. The chosen region extends to fainter magnitudes and is widened to account for the increasing magnitude errors.

2.2 Spectroscopic Data

A more detailed dynamical analysis of Abell 2465 will be presented elsewhere as observations are still ongoing (Wegner et al. In preparation). Redshifts of galaxies centred on Abell 2465 were measured 2007-2009 from the MDM Observatory and the Anglo-Australian Observatory (AAT) before the CFHT images were obtained. The target list was constructed using B and R CCD images from the MDM 1.3 telescope of the inner $10'$ of the cluster and the superCosmos Sky Survey (SSS),³ which is based on the UK Schmidt B_JRI photographic plates, to cover the entire one degree square centred on the cluster. Sources flagged as galaxies (i.e. CLASS = 1), were included. The zero points of the SSS photographic photometry were adjusted using the CCD data and sources with colour indices, $1.5 \leq (B_J - R_2) \leq 2.4$ which is centred on the red sequence were included in the list.

Redshifts of 359 galaxies were obtained. Of these, 160 have redshifts in the range $70000 < cz < 77000 \text{ km s}^{-1}$ which includes the cluster members. Of the remainder, 107 lie in the foreground and 92 lie behind the cluster. An additional 57 objects were stars and 93 targets did not have high enough signal-to-noise to secure a redshift.

The MDM observations were obtained with a long slit

at the 2.4 m Hiltner telescope. The spectrograph was rotated in order to acquire multiple galaxies, ranging in number typically from between three and ten objects, simultaneously. In 2007 and 2009, the CCDS spectrograph with a 150 lines/mm grating was used. In 2007, the slit width was $1''.3$ and the wavelength covered was $\lambda\lambda 4046 - 7245$. In 2009, a $2''.1$ slit and wavelength coverage of $\lambda\lambda 4671 - 8591$ were used. These setups yielded FWHM resolutions of 11 and 16 Å, measured from night sky lines. In 2008, the MKIII spectrograph, a $2''.36$ slit, and a 300 lines/mm grism covering $\lambda\lambda 4358 - 8716$ were employed, yielding a FWHM resolution of 17 Å.⁴ Three 20 minute integrations were usually made with interspersed wavelength calibrations. Standard data reductions of the CCD spectra were carried out using IRAF, which includes bias subtraction, flat fielding, and wavelength calibration.

The largest number of redshifts was collected through the Service Observing Programme of the AAT with the AAOmega multi-object spectrograph in 2008 May 31 and July 25. Four 30 minute exposures were obtained each night. The AAOmega simultaneously observes the blue and red portions of the spectrum. For the blue, the 580V grating which covers $\lambda\lambda 3700 - 5800$ was employed while for the red, the 385R grating that extends across $\lambda\lambda 5600 - 8800$ was used. The instrument nominally has 392 fibres of $2''.0$ diameter and this setup gives a FWHM resolution of about 6 Å. Wavelength calibration, flat fields, and biases were provided and the preliminary reductions were facilitated using the 2DFDR programme.⁵ Subsequent reductions were done with IRAF.

Absorption line measurements employed the Tonry & Davis (1979) cross-correlation method contained in the IRAF task FXCOR. KIII stars were initially used for velocity standards with the MDM data, but for final reductions, the BCG galaxies in Abell 2465 were used. These objects are in Table 2 at $\alpha_{J2000} = 339.85236, 339.91864$ and 339.91916 . All spectra with the Tonry & Davis $R < 3$ and for which features could not be verified by eye were rejected.

Emission lines were used when an absorption line measurement could not be obtained. If both emission and absorption velocities could be secured, they were averaged. The strong H and K lines of Ca II were also used as a check. A substantial number of galaxies had emission lines in their spectra that could be accurately measured and were used to verify the velocity scales of the AAT data. Compared to the imaging data, all spectra are of bright cluster members; the number of objects observed in the current set of spectra drops off rapidly fainter than $i' = 20$ which is a rough estimate of the limit of the current spectra.

Table 2 presents a subset of the redshift data for cluster members in the central regions of Abell 2465 which was used in this paper. Columns 1 and 2 are the galaxies' coordinates, Columns 3 and 4 are the measured heliocentric redshift and its error, Column 5 gives the number of spectra, Column 6 states which telescope was used; A is for the AAT and M

⁴ Further details of these instruments can be found on the MDM Observatory web-page: <http://www.astro.lsa.umich.edu/obs/mdm/technical/index.html>

⁵ Descriptions of the AAOmega can be found at: <http://www.aao.gov.au/local/www/aaomega/>

³ <http://www.wfau.roe.ac.uk/ssss/index.html>

Table 2. Redshifts for cluster members in the central regions of Abell 2465 SW and NE

α_{J2000}	δ_{J2000}	cz (km s ⁻¹)	εcz (km s ⁻¹)	N_{obs}	Tel.	i' (mag.)	$w_i(SW)$	$w_i(NE)$
339.75808	-5.79450	72990	29	1	A	19.231	0.6540	0.3450
339.78149	-5.75772	72540	196	1	A	19.114	0.6790	0.3200
339.79600	-5.79644	73972	37	1	M	18.894	0.7900	0.2090
339.79696	-5.83281	72338	63	1	A	18.394	0.7280	0.2710
339.80219	-5.78419	73571	177	1	M	19.456	0.8310	0.1690
339.80887	-5.74450	73949	9	1	A	19.269	0.7130	0.2860
339.81299	-5.75097	72992	35	1	M	18.626	0.7900	0.2090
339.81662	-5.79906	73586	192	1	A	18.795	0.9170	0.0820
339.82141	-5.70861	73235	139	1	M	19.976	0.5470	0.4520
339.82428	-5.74400	74204	108	1	M	19.846	0.7180	0.2810
339.82697	-5.74289	74196	45	1	M	19.094	0.7220	0.2780
339.83484	-5.82644	72171	213	1	M	18.867	0.8000	0.1990
339.83499	-5.73975	74032	115	1	A	19.031	0.7060	0.2940
339.83524	-5.75508	73520	110	1	M	18.984	0.8800	0.1190
339.83542	-5.82269	72566	10	1	A	17.138	0.9230	0.0760
339.84021	-5.82114	74470	58	2	2M	18.410	0.8820	0.1170
339.84076	-5.80964	74604	113	1	A	18.826	0.8850	0.1140
339.84311	-5.75219	72357	150	1	M	18.301	0.8370	0.1620
339.84338	-5.79100	72788	69	2	1A1M	18.886	1.0000	0.0000
339.84662	-5.75625	73655	14	1	M	18.652	0.9140	0.0850
339.84725	-5.86158	72244	125	1	M	18.225	0.7260	0.2730
339.84738	-5.74164	74152	40	1	A	18.629	0.6980	0.3010
339.84784	-5.81222	73476	30	1	M	17.460	1.0000	0.0000
339.85004	-5.74921	73575	93	2	2M	18.565	0.7930	0.2060
339.85236	-5.78806	73533	1	5	2A3M	16.534	1.0000	0.0000
339.85291	-5.78672	73522	126	1	M	19.512	1.0000	0.0000
339.85416	-5.78444	72242	14	2	2M	17.879	1.0000	0.0000
339.85526	-5.78358	72094	171	1	M	18.061	1.0000	0.0000
339.85626	-5.78508	73561	113	1	M	18.351	1.0000	0.0000
339.85654	-5.78022	73429	30	1	M	18.370	1.0000	0.0000
339.85669	-5.76196	72686	141	2	1A1M	18.528	0.9430	0.0560
339.85796	-5.66972	72573	240	1	M	18.873	0.3360	0.6630
339.85922	-5.77811	72956	242	1	A	19.912	0.9610	0.0380
339.86432	-5.88822	73537	76	1	M	18.776	0.6480	0.3510
339.86508	-5.73889	73976	24	1	A	20.007	0.5240	0.4750
339.86609	-5.79450	73592	23	1	M	17.487	1.0000	0.0000
339.86728	-5.76581	72014	40	1	A	18.565	0.8410	0.1580
339.87332	-5.80614	73914	168	1	A	19.535	0.9330	0.0660
339.87396	-5.76278	74040	147	1	M	19.918	0.7570	0.2420
339.87462	-5.69311	73193	28	2	2A	19.127	0.1460	0.8530
339.88004	-5.67217	73317	160	1	M	19.517	0.1810	0.8180
339.88092	-5.75026	74626	158	1	A	17.853	0.5010	0.4980
339.88297	-5.68617	72702	190	1	M	19.378	0.1810	0.8180
339.88324	-5.68225	73647	36	1	M	18.848	0.1070	0.8920
339.88464	-5.68631	73239	114	1	M	19.236	0.1010	0.8980
339.88464	-5.76603	73244	8	1	M	18.565	0.7930	0.2060
339.88483	-5.76292	73306	22	1	A	19.680	0.7460	0.2530
339.88586	-5.68911	73326	42	1	M	21.910	0.1390	0.8600
339.88846	-5.80075	74298	76	1	M	19.315	0.8170	0.1820
339.89209	-5.80678	73395	7	1	M	20.391	0.8510	0.1490
339.89420	-5.81267	73756	58	1	M	18.386	0.8430	0.1560
339.89771	-5.80597	74019	45	1	A	19.407	0.7810	0.2180
339.89868	-5.82036	73171	47	1	M	19.533	0.7860	0.2130
339.89879	-5.69512	75000	74	3	1A2M	17.497	0.0070	0.9920
339.89908	-5.82653	74029	44	1	M	20.867	0.7320	0.2670
339.89958	-5.70617	73388	179	2	1A1M	18.445	0.0000	1.0000
339.90045	-5.83000	74071	78	1	A	19.588	0.7190	0.2800
339.90379	-5.75611	73388	130	1	M	18.578	0.3500	0.6490
339.90479	-5.74742	73297	56	1	A	18.833	0.1950	0.8050
339.90482	-5.67711	75208	54	1	A	18.703	0.1820	0.8170
339.90521	-5.68931	74709	51	1	M	18.841	0.0830	0.9160
339.90805	-5.72461	73311	126	1	M	18.096	0.0000	1.0000
339.90917	-5.77036	73698	13	1	M	19.507	0.5080	0.4910
339.90925	-5.77828	74085	35	1	A	19.569	0.5670	0.4320

Table 2 – *continued* Redshifts for cluster members in the central regions of Abell 2465 SW and NE

α_{J2000}	δ_{J2000}	cz (km s $^{-1}$)	εcz (km s $^{-1}$)	N_{obs}	Tel.	i' (mag.)	$w_i(SW)$	$w_i(NE)$
339.90976	-5.75339	73857	80	1	A	18.885	0.2480	0.7510
339.90982	-5.73439	73220	185	1	M	20.117	0.0970	0.9020
339.91043	-5.69272	74636	48	1	M	18.059	0.0020	0.9970
339.91147	-5.81964	72128	64	1	A	17.652	0.7160	0.2830
339.91183	-5.68417	74958	4	2	2M	18.740	0.1180	0.8810
339.91187	-5.63333	73217	115	1	A	19.722	0.2760	0.7230
339.91226	-5.83436	72025	40	1	A	20.034	0.6270	0.3720
339.91293	-5.79492	73180	37	1	A	17.488	0.6930	0.3060
339.91388	-5.73789	73060	23	1	M	18.805	0.0720	0.9270
339.91403	-5.73167	73361	76	1	M	19.879	0.0030	0.9960
339.91522	-5.73214	72576	40	3	3M	18.076	0.2090	0.7900
339.91864	-5.72389	73044	31	3	1A2M	17.070	0.0000	1.0000
339.91916	-5.72181	74061	119	2	2M	17.898	0.0000	1.0000
339.92084	-5.73189	74847	76	1	M	19.318	0.1950	0.8040
339.92203	-5.73417	74721	121	1	M	18.378	0.1010	0.8980
339.92871	-5.74033	73186	93	1	M	18.394	0.0890	0.9100
339.92899	-5.70703	72670	142	1	M	19.281	0.0450	0.9540
339.93253	-5.72194	72745	74	2	1A1M	17.960	0.0000	1.0000
339.93542	-5.67039	73467	131	1	M	19.377	0.1130	0.8860
339.93896	-5.75525	73063	63	2	1A1M	19.138	0.2750	0.7240
339.94089	-5.71742	73814	21	1	M	18.773	0.0240	0.9750
339.94403	-5.65308	74188	150	1	M	18.526	0.2250	0.7740
339.94528	-5.76256	73828	42	1	A	19.616	0.3020	0.6970
339.94589	-5.64414	74096	264	1	M	20.321	0.3160	0.6830
339.94791	-5.62986	73698	77	1	M	17.763	0.2930	0.7060
339.95475	-5.79149	73571	138	3	2A1M	19.103	0.4570	0.5420
339.96658	-5.75661	73555	46	1	A	17.582	0.2830	0.7160
339.96689	-5.64408	73549	75	1	A	20.273	0.3160	0.6830
340.00000	-5.73803	73528	11	1	A	18.061	0.3430	0.6560

is for MDM, Column 7 is the i' magnitude from §2, and Columns 8 and 9 are the fuzzy weights explained in §3.1 below.

3 MASS ESTIMATES OF THE TWO CLUMPS

An estimate of the virial masses of the two clumps is made in the following. Although one can question the validity of this method, Poole et al. (2006) find that colliding clusters regain virial equilibrium relatively quickly. Takizawa, Nagino, & Matsushita (2010) employ N-body simulations to compare virial mass estimates for colliding galaxy clusters and find that when the mass ratio is larger than 0.25, the estimated virial masses can be a factor too large, and in general, X-ray mass estimates are more accurate. While for the present, the question of virial equilibrium will be avoided, one should note that the virial masses found in §3.3 agree within their errors with those obtained from X-ray scaling relations.

3.1 Fuzzy Clustering

A difficulty in dealing with galaxy clusters with overlapping components is the separation of the members of each sub-clump, when not all the phase space information can be known. For galaxy clusters with multiple components, this becomes a problem when it is necessary to resolve the members of the sub-clumps as in the present case of Abell 2465. This subject belongs to the wider realm of cluster analysis (e.g., Anderberg 1973; Höppner et al. 1999; Kaufman &

Rousseeuw 2005; Gan, Ma, & Wu 2007) and many authors have discussed solutions to the galaxy cluster problem, each with some success in their particular case, but at present, no single method is known to give a complete and secure solution. Pinkney et al. (1996) have reviewed several tests.

Notable examples include the Δ -statistic (Dressler & Schechtman 1988), the DEDICA program of Ramella et al. (2007), and additional methods described in the papers of Salvador-Solé, Sanromà, & González-Casado (1993), Tully (1980), Serna (1996), and Diaferio (1999). Tully (1980), Serna (1996), and Diaferio (1999) employed the single-link hierarchical clustering technique and constructed dendrograms. For the affinity parameter, Tully took the inverse of the attractive force, while Serna (1996) and Diaferio (1999) used the projected binding energy between two galaxies, i and j :

$$E_{ij} = -G \frac{m_i m_j}{|r_i - r_j|} + \frac{1}{2} \frac{m_i m_j}{(m_i + m_j)} (v_i - v_j)^2, \quad (1)$$

where m_i , r_i , and v_i are the mass, position on the sky, and the redshift for the i th galaxy.

The k-medoid method (KMM) has been employed by several investigators (e.g., Colless & Dunn 1996; Kriessler & Beers 1997; Yuan et al. 2005) to separate cluster members. Kriessler & Beers' KMM results compared favourably with previous analyses of 56 clusters. The KMM assigns each object uniquely to one cluster (Kaufman & Rousseeuw 2005), termed 'hard clustering,' but given the observational errors and ambiguities of the data, it is unlikely that such a unique assignment is always accurate.

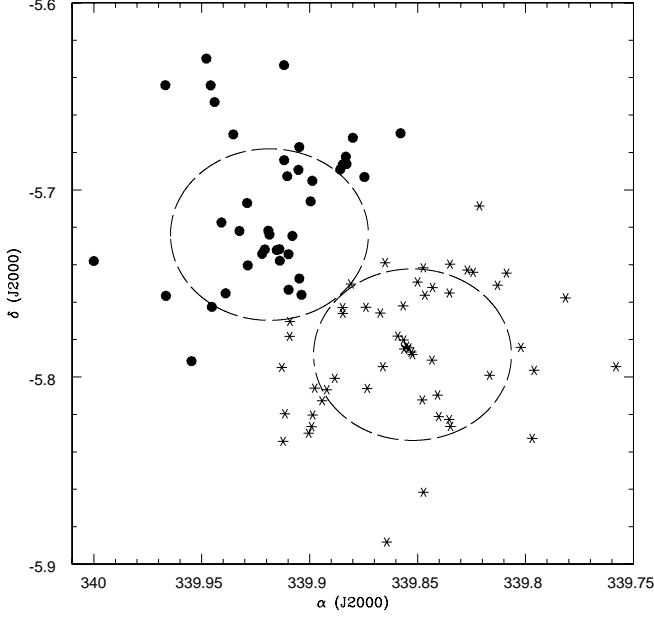


Figure 4. Distributions of the galaxies in Abell 2465 with measured redshifts and assigned to each clump using the hard clustering (i.e. membership coefficient, $w_i \geq 0.5$). Filled circles and asterisks denote the NE and SW clumps respectively. The dashed circles are centred on the BCG of each clump near the X-ray centres and have radii of $2'.75$ or 0.63 Mpc which is half the distance between the two centres.

Consequently, the method of fuzzy analysis was explored to separate the cluster members of Abell 2465 (e.g., Sato et al. 1997; Höppner et al. 1999; Kaufman & Rousseeuw 2005; Miyamoto et al. 2008). Fuzzy clustering generalizes the KMM and permits ambiguity in cluster membership by providing a ‘membership coefficient,’ w_i , for each object, i , running from 0% for a non-member to 100% for a member of only one cluster. Assigning an object uniquely to a cluster by its largest membership coefficient (i.e. $w_i \geq 0.5$) returns the hard clustering result.

The fuzzy analysis algorithm (FANNY) and program of Kaufmann & Rousseeuw (2005) were employed for the analysis of the cluster members. As in the methods above, one chooses the number of clusters, k , an affinity between pairs of objects (i, j) and derives a dissimilarity matrix with elements $d(i, j)$. This was obtained by defining a projected binding energy:

$$b_{ij} = \frac{-m_i m_j}{|r_i - r_j|} + 1.162 \times 10^{-4} S \frac{m_i m_j}{(m_i + m_j)} (v_i - v_j)^2, \quad (2)$$

using r_i in megaparsecs, v_i in km s^{-1} , and m_i in units of $10^{12} M_\odot$. A scaling factor, S , was employed to lower the weight of the second term. The m_i were derived from the i' magnitudes of the galaxies using the formula of Cappellari et al. (2006) for the I -band, $(M/L) = (2.35)(L_I/10^{10} L_{I,\odot})^{0.32}$ and $I = i' - 0.61$. The b_{ij} were converted to dissimilarities using $d(i, j) = \frac{1}{2}[1 + \text{erf}(b_{ij})]$, which gives $0 \leq d(i, j) \leq 1$ whereby nearby and tightly bound pairs with large negative b_{ij} have small dissimilarities, and distant unrelated pairs are assigned positive dissimilarities.

Figure 4 shows the resulting distribution of the galaxies

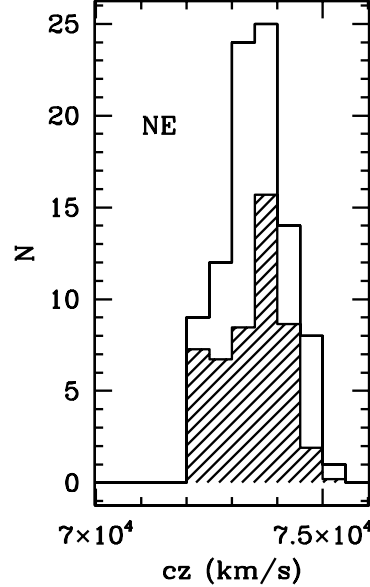
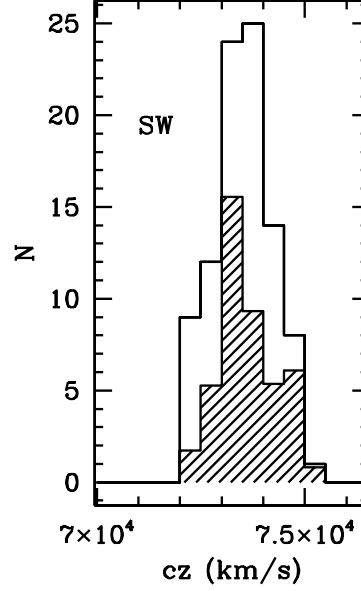


Figure 5. Histograms of redshifts of the two Abell 2465 clumps based on the fuzzy clustering. Upper unfilled histogram shows the whole sample. Lower shaded histograms show the weighted velocity distributions from the fuzzy weights that were used in determining the virial masses.

in the two clumps and Figure 5 has histograms of their corresponding velocities. In this hard clustering presentation, the result is approximately what one intuitively expects as the galaxies are divided mostly into the two groups near the outlines of the circles in Figure 4 and using the fuzzy weights in Figure 5 the difference in the velocity peaks can be seen.

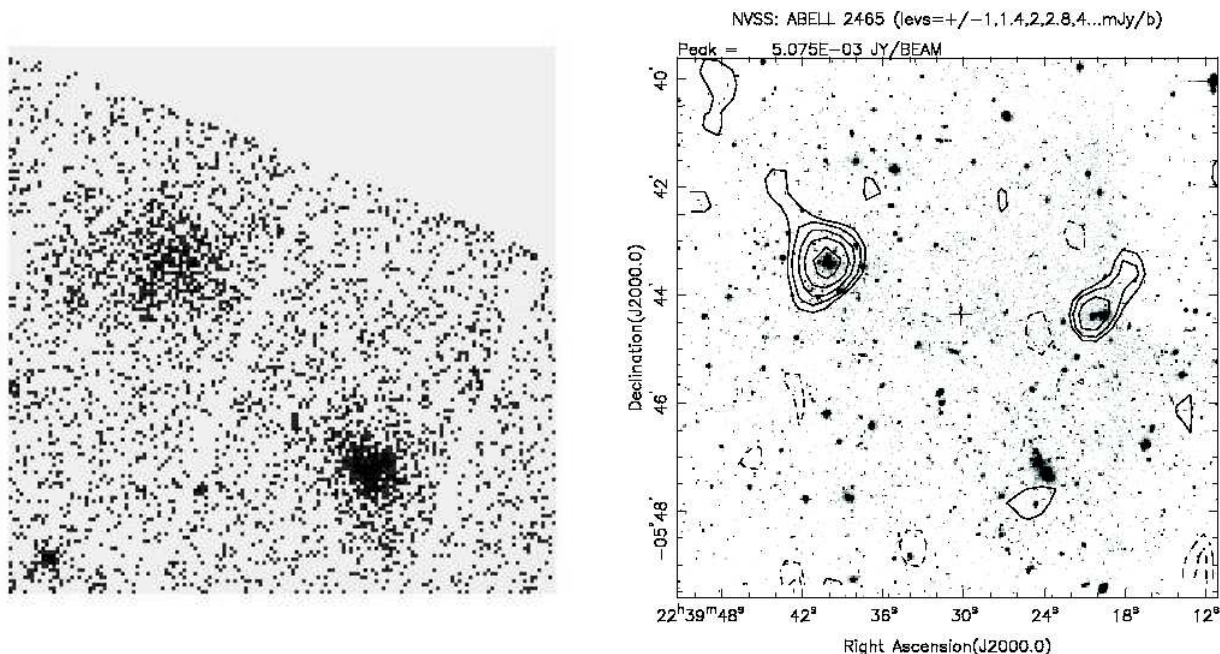


Figure 6. The X-ray and 1.4 GHz radio images of Abell 2465. Both are at the same scale. The vertical border of each box represents 2.3 Mpc at the distance of Abell 2465. North is at the top and East is to the left. (Left) 1-2 keV X-ray data near the cluster from a portion of archived XMM image 0149410401003 from project of PI S. Mathur. (Right) 1.4 GHz contours provided by the NVSS Postage Stamp Server superimposed on the i' image of this paper.

3.2 The Virial Masses

Virial masses were estimated from the redshift data following e.g., Carlberg et al. (1996) and Girardi et al. (1998). All quantities were referred to the rest frame of the clusters. A weighted virial mass estimator was used which reduces to the Heisler, Tremaine, & Bahcall (1985) eq. 4 for unit weights:

$$M_v = \frac{3\pi \sum_i w_i}{2G} \frac{\sum_i w_i V_{zi}^2}{\sum_{i < j} w_i w_j / R_{\perp,ij}}, \quad (3)$$

where the w_i are the fuzzy clustering weights, $V_{zi} = (V_i - \bar{V})/(1 + \bar{z})$ and $R_{\perp,ij}$ is the angular size distance between two galaxies i and j .

Galaxies within 1.4 Mpc of the clump centres and with redshift velocities $72000 < V_{zi} < 76000 \text{ km s}^{-1}$ were used to obtain M_v . The galaxies with their redshifts that were used are given in Table 2.

For the NE clump, there are $\sum_i w_i = 49$ galaxies within this radius while for the SW clump, $\sum_i w_i = 44$. The resulting virial masses, M_v , for NE and SW respectively are: where the uncertainties are jackknife errors. Figure 5 shows the histograms of the velocities. The corresponding mean redshifts for the two clumps are $\bar{V}_{NE} = 73593 \pm 102 \text{ km s}^{-1}$ and $\bar{V}_{SW} = 73388 \pm 109 \text{ km s}^{-1}$, which yields a velocity difference of $\Delta V = 205 \pm 149 \text{ km s}^{-1}$.

The virial radii, according to the formula $r_{200} = \frac{\sqrt{10}}{3} \frac{\sigma^2}{H(z)^2}$ (Carlberg et al. 1996) are $1.21 \pm 0.11 \text{ Mpc}$ (NE) and $1.24 \pm 0.09 \text{ Mpc}$ (SW). This assumes the virial mass is approximated by $M_{200} = \frac{4}{3}\pi r_{200}^3 \Delta_c \rho_o(z)$, where $\rho_o(z)$ is the critical density at redshift z and Δ_c is the cluster's density enhancement, set equal to 200.

The masses of the two clumps calculated using the hard clustering weighting ($w_i = 0$ or 1) are 3.7 ± 0.7 and $3.0 \pm 0.7 \times 10^{14} M_\odot$ respectively for the SW and the NE clumps. For comparison, the redshift difference between the two BCGs near the centres of the NE and SW clump is 489 km s^{-1} . The unweighted average of 149 cluster members inside one degree of the cluster centre is $73530 \pm 58 \text{ km s}^{-1}$.

A correction to M_v is required due to the whole cluster not being included in the calculation (e.g., Girardi et al. (1998 and references therein). This depends on the galaxy and velocity dispersion distributions with radius. A $c = 6$ NFW profile was assumed and it was found that the correction could be neglected for the present data.

3.3 Comparison with X-ray Masses

The virial masses can be compared with those from X-ray scaling relations. Both ROSAT and XMM-Newton observed Abell 2465 serendipitously. Contours of the ROSAT data are in Perlman et al. (2002). Figure 6 shows the XMM image alongside the 1.4 GHz radio data discussed in §3.4. Averaging the unabsorbed ROSAT values in the (0.5-2.0) keV band according to Vikhlinin et al. (1998) and Perlman et al. (2002) gives $f_X = 3.605 \times 10^{-13}$ and $2.53 \times 10^{-13} \text{ ergs sec}^{-1} \text{ cm}^{-2}$ respectively for the NE and SW clumps. The XMM-Newton values taken from the 2XMMi-DR3 catalogue in the (0.5-2.0) keV band are the ep_2 + ep_3 fluxes and are 2.44×10^{-13} and 2.08×10^{-13} respectively. These were multiplied by 1.07 to correct for absorption, using $n_H = 3.64 \times 10^{20} \text{ atoms cm}^{-2}$, (the mean of the Kalberla et al. (2005) and Dickey & Lockman (1990) values implemented in HEASARC), Wilms et al. (2000) for the X-ray

absorptivity per H atom in the ISM, and a 4 keV Raymond-Smith (Raymond & Smith 1977) 0.3 solar metals model at redshift $z = 0.245$.

Many authorities find scaling relations between X-ray luminosity and mass, temperature, etc. (e.g., Reiprich & Böhringer 2002; Popesso et al. 2005; Rykoff et al. 2008). The results of Popesso et al. (2005) for M_{200} , in the (0.1-2.4 keV) band were adopted. A multiplicative factor of 1.60 was found to bring the ROSAT and XMM (0.5-2.0) keV data into this band using the 4 keV Raymond-Smith model above. With the luminosity distance of 1224 Mpc for Abell 2465, $L_X = 8.94 \pm 1.44 \times 10^{43}$ ergs sec $^{-1}$ for NE and $L_X = 6.84 \pm 0.43 \times 10^{43}$ ergs sec $^{-1}$ for SW. The Popesso et al. (2005) uncorrected relation for mass, $\log M_{200} = [\log(L_X/10^{44}) + 1.15]/1.58$ yields:

$$4.4 \pm 0.6 \times 10^{14} M_\odot \text{ and } 3.6 \pm 0.2 \times 10^{14} M_\odot$$

for the NE and SW clumps respectively.

The $L_X - T$ relation, $\log T_X = [\log(L_X/10^{44}) + 2.06]/3.30$ (Popesso et al. 2005), gives temperatures for NE and SW of:

$$4.1 \pm 0.3 \text{ keV and } 3.75 \pm 0.2 \text{ keV,}$$

where the errors include the range in L_X and the scatter of the relation. The mass weighted $M_{200} - T_X$ relation found by Sanderson et al. (2003) gives nearly identical values of T_X .

Given T_X , the cooling times of the two clumps provide additional information. The bremsstrahlung cooling time for cluster gas of temperature T and hydrogen density, n_p is:

$$t_{cool} = 8.5 \times 10^{10} \left(\frac{T}{10^8} \right)^{\frac{1}{2}} \left(\frac{n_p}{10^{-3} \text{ cm}^{-3}} \right)^{-1} \quad (4)$$

(Sarazin 1986; eq. 5.23). At the current temperature of $T \approx 4$ keV, n_p can be estimated from

$$\varepsilon = 3.0 \times 10^{-27} \left(T_g \right)^{\frac{1}{2}} n_p^2, \quad (5)$$

Sarazin (1986; eq. 5.21). Using that $L/2 \approx \varepsilon \frac{4}{3} \pi r_c^3$ and the core radii $r_c = 42$ and 130 kpc for SW and NE (Vikhlinin et al. 1998), $t_{cool} \approx 4$ and 20 Gyr for SW and NE respectively. This indicates that SW is a cooling core (CC) cluster. This shorter t_{cool} in the SW subcluster results from its smaller r_c and is consistent with studies of CC clusters showing they have core radii $r_c \lesssim 100$ kpc (e.g., Chen et al. 2007). As already noted, there is no evidence for strong AGN activity in either member of Abell 2465. It is tempting to identify the CC as a result of the cluster's merger, but O'Hara et al. (2006) argued that major mergers do not evolve cooling cores from their study of the scatter in scaling relations. However, ZuHone & Markevitch (2009) found that 'sloshing' produced in mergers could be a source of heating in cluster cores.

3.4 Radio data

Abell 2465 appears to be detected in the 1.4 GHz NRAO VLA Sky Survey (NVSS; Condon et al. 1998). The radio contours are shown in Figure 6 where they are superimposed on the i' image. A source with peak flux 6.2 ± 0.6 mJy falls near the NE component and appears to be a radio halo. A

second elongated object with a peak flux of 3.1 ± 0.4 mJy is near the three early-type cluster members located about 3 arcmin north of the SW clump. No significant source lies in the SW optical component. If the two radio sources are at the distance of Abell 2465, their luminosities are 11×10^{23} and 6×10^{23} W Hz $^{-1}$. These are within the range of luminosity, temperature, and size for diffuse radio halos and relics summarized by Feretti (2002). The radio halo is centred near the NE subcluster which might identify it as the primary component of Abell 2465.

A more detailed analysis of the X-ray and radio data will be given elsewhere (Wegner & Johnson, in preparation).

3.5 Cluster Velocity Dispersion Measurements

The run of radial velocity dispersion with radius contains information on the dynamics of the clusters. The results of measurements for the two clumps are shown in Figure 7, where the fuzzy weighting was employed and errors given are jackknife errors.

The simplest case solves the spherical Jeans equation for the anisotropy parameter, β , where $\beta = 0$ for isotropic orbits, and $\beta = 1$ is the non-physical limiting case of purely radial orbits. The aperture values of σ are shown in Figure 7, where the formulae of Lokas & Mamon (2001) were used for the mean velocity dispersion inside an aperture of radius R :

$$\sigma_{ap}^2(R) = \frac{S^2(R)}{M_p(R)}, \quad (6)$$

where M_p is described in equation (8) and S^2 is:

$$S^2(R) = c^2 g(c) M_v \left\{ \int_0^\infty \frac{\sigma_r^2(s, \beta) s}{(1 + cs)^2} \left(1 - \frac{2\beta}{3} \right) ds + \int_R^\infty \frac{\sigma_r^2(s, \beta) (s^2 - \tilde{R}^2)^{1/2}}{(1 + cs)^2} \left[\frac{\beta(\tilde{R}^2 + 2s^2)}{3s^2} - 1 \right] ds \right\}, \quad (7)$$

where $s = r/r_v$, $M_v = \frac{4}{3} \pi r_v^3 \Delta_c \rho_o(z)$ is the virial mass, and the other quantities are defined in §5. Lokas & Mamon (2001) give analytical expressions for $\sigma_r^2(s, \beta)/V_v^2$ for constant $\beta = 0, 0.5$, and 1 and the Osipkov-Merritt (OM) model (Osipkov 1979; Merritt 1985), $\beta_{OM} = s^2/(s^2 + s_a^2)$, which are used to evaluate the integral.

Figure 7 compares curves for three values of β with the observed values in terms of the virial radius circular velocity $V_{vir}^2 = GM_v/r_v$. OM models with $s_a \approx \frac{4}{3}$ lie nearby the lower β curves and are not shown. Values of V_{vir} of 763 km s $^{-1}$ and 722 km s $^{-1}$ were adopted for the NE and SW clump respectively. It can be seen that the most consistent anisotropy values are low, near $\beta = 0$, but agreement with $\beta = 1.0$ is ruled out for small radii. These values of V_{vir} place the data points onto the 0 and 0.5 β curves at the largest observed radii. Using the masses and radii found above, the corresponding values would be 1077 and 1043 km s $^{-1}$, but given the error in the value of M_v/r_v which give V_{vir} , these differ from the adopted values less than two standard deviations.

The behavior of β in the dark matter component of galaxy clusters has been investigated by several authors with the idea that this can probe its properties. For Λ CDM, Thomas et al. (1998) found that $\beta \leq 0.3$ inside the virial radius. Hansen & Piffaretti (2007) obtained similar values for two clusters as did Host (2009) and Host et al. (2009) for

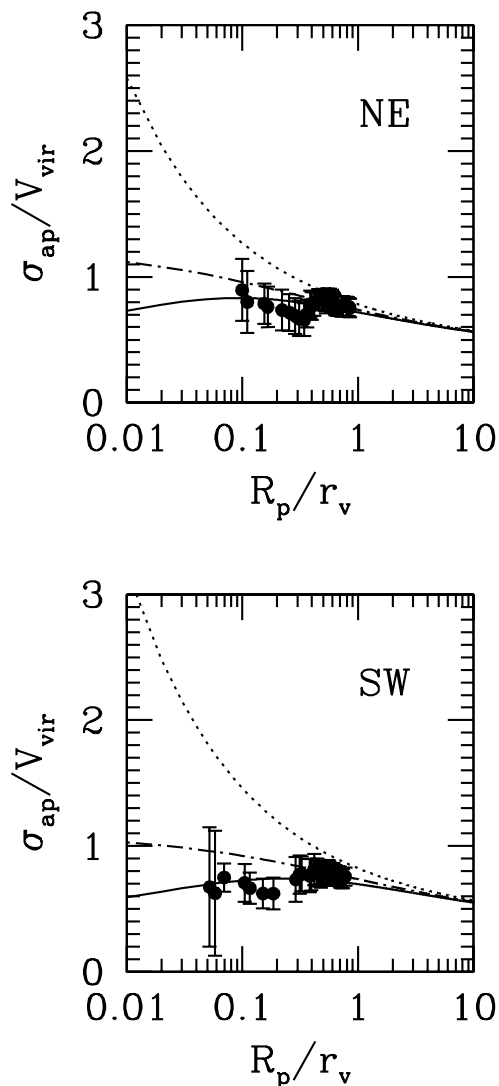


Figure 7. Radial profiles of the aperture-velocity dispersions for the two clumps in Abell 2465. The abscissae give the projected radial distances relative to the virial radius, r_v , and the ordinates are the velocity dispersions and their errors relative to the circular velocity, V_{vir} , defined in the text inside of R_p . The different curves are for NFW models with $c = 10$ (SW) and $c = 4$ computed using Lokas & Mamom (2001). Dotted curve: $\beta = 1$, dot-dash curve denotes $\beta = 0.5$, and solid curve is $\beta = 0$.

several X-ray clusters. The values of β for the subclusters of Abell 2465 are consistent with these results.

3.6 Emission Line Galaxies in Abell 2465

Of the 149 galaxies in Abell 2465, observed spectroscopically with redshift $70000 \leq cz \leq 76000 \text{ km s}^{-1}$, and within one degree of the cluster centres, 55, or 37%, show detectable H α emission of which 38 also have measureable [N II], H β , and [O III] and can be plotted in the diagnostic diagram that separates star forming galaxies, liners, and AGNs. Equiva-

Table 4. Additional galaxies with detected H α emission

α_{J2000}	δ_{J2000}	Tel.	Type
339.58828	-5.93192	A	E
339.76129	-5.87131	A	S0 pec
339.79599	-5.79644	M	Sp tail
339.82037	-5.85808	M	S0 asy
339.84738	-5.74164	A	E
339.85510	-5.78122	M	SBc asy
339.86731	-5.76581	A	E
339.88293	-5.68617	M	S0
339.88461	-5.76603	M	S0
339.88842	-5.80075	M	S0
339.90484	-5.74722	A	S0
339.92083	-5.73192	M	E
339.93524	-5.67008	A	S0
339.93899	-5.67408	M	Sa
339.94891	-5.62542	M	E
340.10977	-5.80497	A	Sp

lent widths were measured using the IRAF SPLIT routine and independently measured twice to estimate errors. The H α and H β equivalent widths were adjusted for underlying absorption. Following Wegner & Grogin (2008). H α was corrected by adding 2.32 Å to the measured emission and 2.02 Å was added to the H β emission, which are the absorption equivalent widths of these lines from galaxies that appear free of emission.

The resulting line ratios and their errors are given in Table 3, where Columns 1 and 2 are the coordinates of the galaxies. Columns 2, 3, 4, and 5 give the line ratio measurements and their errors. In Column 6 A and M denote whether AAT or MDM spectra were measured, and the last column is an estimated morphological type.

The morphological types of the emission line galaxies were estimated from the i' image. The largest proportion of these appeared to be disturbed single objects without a visible companion. At least 24 or 44% have unusually asymmetrical disks or spiral arms. Only about six of these galaxies have obvious companions or tidal tails.

The positions of the galaxies that have detected H α emission, but the other emission lines were too faint to place them in the diagnostic diagram, are listed in Table 4 along with their morphologies.

Figure 8 shows the diagnostic diagram. The line separating the Seyfert and liner regions is that given in Yan et al. (2006). The solid and dashed curves demarcating the edge of the star-forming region are from Kewley et al. (2001) and Kauffmann et al. (2003). The emission line galaxies in Abell 2465 are nearly all star-forming objects. Only four objects lie on the border of the liner or Seyfert region. There are no definite Seyferts or AGN activity dominating either clump.

The emission line galaxies prefer to sit between the two subclusters with more near the SW clump. In Figure 9, the left panel shows the positions of all spectroscopically verified cluster members. The right panel plots only emission line objects and is an enlargement of the centre. The X-ray centres from Table 1 are indicated as crosses. The line passing through the centres approximates the cluster's axis, and the lines labeled A, B, and C define stripes running perpen-

Table 3. Line ratio data for the emission line galaxies shown in Figure 8

α_{J2000}	δ_{J2000}	$\log[\text{NII}]/\text{H}\alpha$	$\varepsilon \log[\text{NII}]/\text{H}\alpha$	$\log[\text{OIII}]/\text{H}\beta$	$\varepsilon \log[\text{OIII}]/\text{H}\beta$	Tel.	Type
339.45346	-6.18531	-0.499	0.021	-0.217	0.501	A	Sp
339.47983	-6.20242	-0.562	0.036	0.435	0.290	A	S0 pec
339.64358	-5.61342	-0.320	0.016	-0.173	0.460	A	Sa asy
339.64612	-5.74183	-0.353	0.012	0.049	0.251	A	S0 pec
339.65378	-6.16689	-0.077	0.018	0.091	0.264	A	S0
339.68289	-5.83781	-0.376	0.009	-0.410	0.193	A	S0 pec
339.68362	-5.92178	-0.631	0.038	0.419	0.318	A	S0
339.68655	-5.88831	-0.416	0.039	0.127	0.064	A	S0 asy+S0
339.69240	-5.92532	-0.671	0.036	0.205	0.122	2A	Sc
339.74338	-5.94525	-0.587	0.083	-0.038	0.011	A	Sp asy
339.75180	-5.98858	-0.297	0.003	0.238	0.315	A	SB0 rings
339.75809	-5.79450	-0.433	0.021	-0.370	0.108	A	Sa asy
339.76382	-5.97494	-0.356	0.036	0.215	0.229	A	SBc asy
339.78741	-5.62375	-0.785	0.003	0.542	0.179	A	Sp edge on
339.80887	-5.74450	-0.482	0.001	0.576	0.442	A	Sa
339.81514	-5.89681	-0.368	0.089	0.417	0.017	MA	S0
339.82657	-5.40069	-0.390	0.033	0.252	0.528	A	Sa asy
339.83768	-5.99783	-0.594	0.054	0.389	0.322	A	S0 (POSS2)
339.84326	-5.75222	-0.339	0.047	0.070	0.236	A	SB0
339.85074	-6.20175	-1.309	0.111	0.720	0.051	A	Sc
339.85663	-5.76189	-0.256	0.001	-0.307	0.079	A	S0 asy
339.85699	-5.89256	-0.602	0.066	0.136	0.344	M	Sa
339.86508	-5.73889	-0.377	0.007	0.273	0.224	A	S0+companion
339.87332	-5.80614	-0.211	0.011	0.409	0.269	A	Sp asy
339.88025	-5.56244	-0.611	0.010	0.303	0.345	A	E+Sp
339.88465	-5.68619	-0.780	0.365	0.523	0.020	2M	Sp+E
339.88483	-5.76292	-0.297	0.013	0.018	0.326	A	SBc
339.88586	-5.68911	-0.912	0.074	0.303	0.298	M	E?
339.89172	-5.60164	-0.517	0.015	0.355	0.499	A	Sb pec
339.89771	-5.80597	-0.366	0.013	-0.135	0.053	A	Sp asy
339.90045	-5.83003	-0.325	0.018	0.535	0.267	M	S0
339.90931	-5.77829	-0.703	0.073	0.283	0.165	AM	Sp tail
339.94437	-5.65339	-0.534	0.016	0.200	0.377	M	S0 pec
339.94528	-5.76256	-0.233	0.053	0.158	0.039	A	Sp asy
340.06308	-5.58347	-0.485	0.068	-0.334	0.041	A	Sb asy
340.06516	-5.62183	-0.465	0.002	0.045	0.011	A	Sa asy
340.10855	-5.57439	-0.497	0.015	0.434	0.382	A	Sa asy
340.12149	-5.95319	-0.366	0.002	-0.494	0.033	A	Sb asy

NOTES TO THE TABLE: asy - one side of object noticeably stronger; pec - disturbed and/or shells

dicular to this axis. The line B marks the distance half way between the two subcluster centres. Using this centre line, of the 39 galaxies in the figure, 24 are on the SW side and 15 are on the NE side. However, the asymmetry is stronger in the central region of the cluster. In strip BC, 13 emission galaxies lie close to the SW centre while only five are near the NE clump in strip AB. For non-emission line galaxies, the corresponding numbers are 20 and 15 galaxies respectively.

This impression of asymmetry between the emission and non-emission line galaxy distributions was tested with the two dimensional Kolmogoroff-Smirnov test (Fasano & Franceschini 1987; Lopes, Reid, & Hobson 2007). Using the ks2D2S programme (Press et al. 1992) for the two-sample test to compare the emission and non-emission samples indicates weakly that the two types of galaxies are slightly different at the 78% significance level.

There are more emission line galaxies near the centre of

Abell 2465 than expected for single galaxy clusters. Balogh et al. (2004) and Rines et al. (2005) find an inverse correlation between the number of emission line galaxies and density in galaxy clusters. For their composite cluster, Rines et al. (2005; figure 2) find that the fraction of galaxies showing emission lines grows from 0 at the centre to 0.12 at $R_p = 0.5R_{200}$ with a mean near 0.06. For Abell 2465, the numbers of galaxies with observed spectra within the circles in Figure 4 which are projected radii of $R_p = 0.53R_{200}$ (0.63 Mpc) from the subcluster centres, are 27 and 22 for SW and NE respectively. The corresponding numbers of emission line galaxies are 9 and 4 giving fractions of emission line galaxies within these circles equal to 0.33 and 0.18. Even allowing for infall interlopers, these fractions appear different for Abell 2465 and the other clusters.

One question is whether the high fraction of star-forming galaxies could be due to a bias in selecting more emission line galaxies because it is easier to get their red-

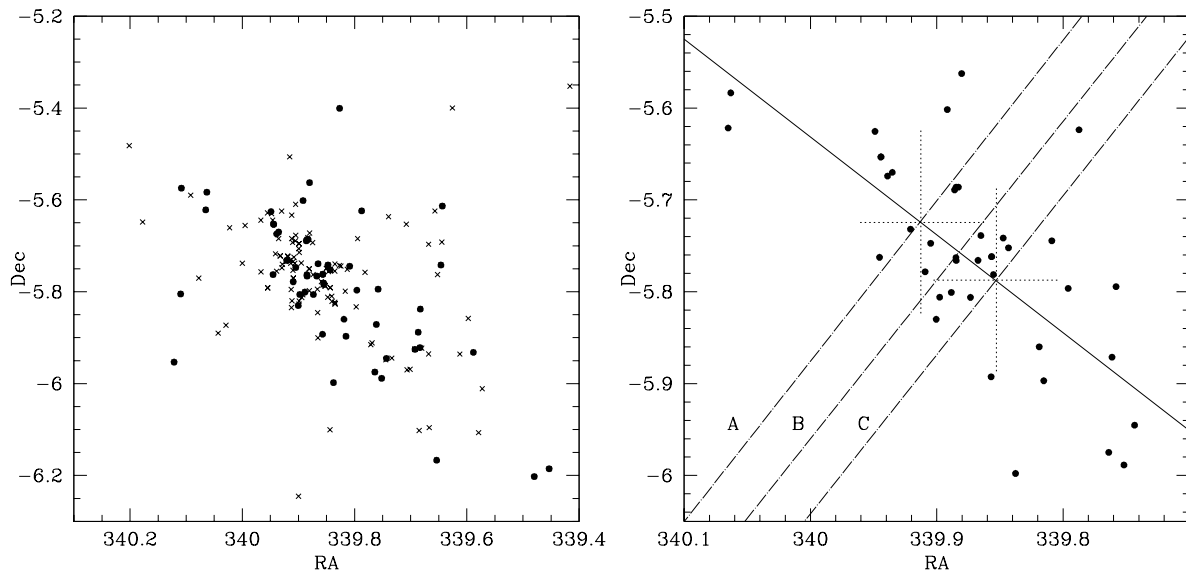


Figure 9. (left) The positions of emission line (solid dots) galaxies with detected $H\alpha$ emission and non-emission line (crosses) galaxies observed in Abell 2465 with $70000 \leq cz \leq 76000 \text{ km s}^{-1}$. (right) Positions of emission line galaxies only, enlarged to show the central portion of the double cluster. The XMM positions of the two X-ray clumps are marked with the crosses.

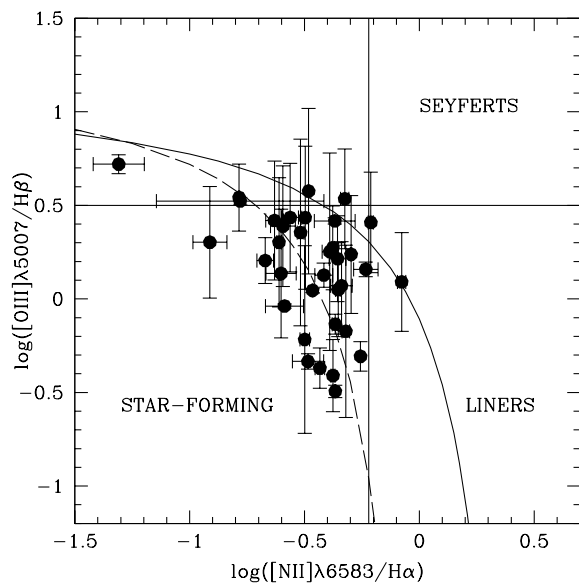


Figure 8. The diagnostic diagram for the emission line galaxies in Figure 9.

shifts. With the current data, this can be answered only roughly given the broad selection criteria and the employment of different spectroscopic instruments. A lower limit to the emission fraction can be estimated using the numbers in §2.2. Firstly, $199/359 = 0.55$ of the galaxies with redshifts should be cluster members. Secondly, if all 93 failed redshift targets are non-emission galaxies, 55% or 51 would be cluster members. Thirdly, adding this to the number of observed cluster galaxies gives the lower limit to the fraction of star-forming cluster members to be $55/(149+51)$, or 28%. This is

still in excess of the fraction, with mean near 6% for single clusters discussed above.

4 THE LUMINOSITY FUNCTIONS OF THE CLUMPS

In this paper, the statistical method of measuring all the galaxy photometry in the field and then subtracting the contribution of the background is employed using the nearly one square degree CFHT images. Photometry of the cluster is confined to the inner $22'.4 \times 18'.0$ portion of the image and the sky background is estimated from the outer part of the images. The data provided by the programme SEXTRACTOR (Bertin & Arnouts 1996; Bertin 2009; Holwerda 2005) described above were employed for separating stars and galaxies. The red sequence of the cluster described in §2.1.3 was used to find the cluster members.

4.1 Background Galaxy Determination

The background, its errors, and the incompleteness were estimated in two steps. First the resulting catalogue of galaxies was binned in magnitude using no colour cut. The outer portion of the CFHT i' image was binned in one magnitude intervals running from $i' = 16.0 - 26.0$. The total area used was 3069 arcmin^2 . The number of detected objects and their colours was 89579. The resulting number counts of the background along with their \sqrt{N} errors are shown in Figure 10, where they are compared to the number counts given by McCracken et al. (2001) from deeper CFHT i' imaging, and Wilson (2003) who used Cousins I band data from the same telescope.

These data agree well for $19 \lesssim i' \lesssim 23$. For i' brighter than 19, small number statistics dominate and it is assumed that the numbers of detections is complete. For i'

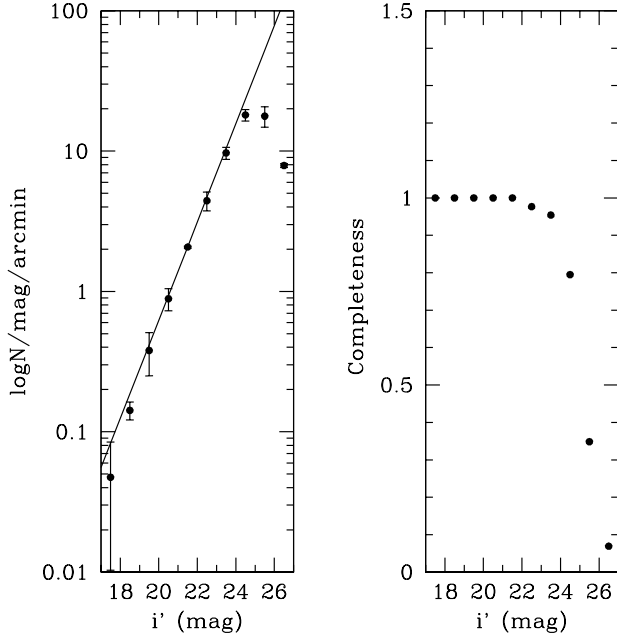


Figure 10. (left) Comparison of i' band number counts found in this study with McCracken's et al. (2001) deeper counts shown as the line. (right) Adopted i' completeness function for the galaxy number counts.

fainter than 23, the completeness is estimated by taking the ratio of the present measurements and the McCracken et al. (2001) relation. The resulting estimate of completeness is also shown in Figure 10 and is 1.0 for $i' = 17 - 22$. For fainter sources, it drops and this relation was adopted for the completeness.

The second step was to apply the same colour cut found for the red sequence to the background data. In addition to counting errors, there are the effects of cosmic variance in the background. To estimate these, the background was divided into four subsections of average 771 arcmin^2 . The variance of these measurements was used to estimate the error in the background.

4.2 Luminosity Functions of the Two Cluster Centres

The luminosity functions (LF) of the SW and NE clumps of Abell 2465 differ. They were obtained for the circular regions within $2'.75$ of the cluster centres as defined in Table 1. Identical colour cuts and the same background subtraction were applied to the data of both clusters. The magnitudes M_I are converted to luminosity using $L_I = 10^{-0.4(M_I - I_\odot)}$ where $I_\odot = 4.08$ (Binney & Merrifield 1998) and $M_I = i' + DM - A_I - K_I(z)$, using the data in Table 1. Bins fainter than $i' = 25$ were rejected due to the large incompleteness correction. The results shown in Figure 11, where the error bars include both background and counting errors, show a significant difference between the two clumps, although both are within the range of luminosity functions found for different clusters.

The bright portions of the two LFs are similar, but the SW clump has a substantially larger number of galaxies

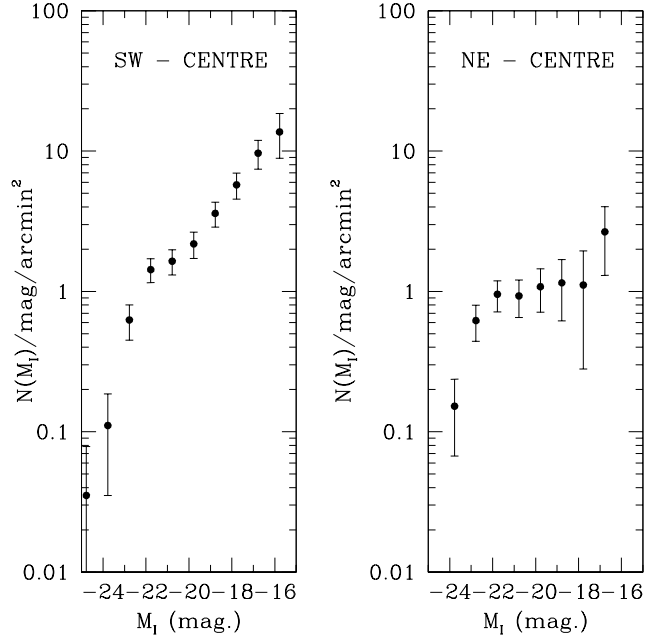


Figure 11. Luminosity functions for the central regions ($R_p < 0.63 \text{ Mpc}$ or $2.75'$) of the SW and NE clumps.

Table 5. Relative Normalization factors for the luminosity functions and assumed $(B - I)$ colours

	E	S0	Sp	dE
$(B - I)$	3.16	2.79	2.16	2.5
SW clump	0.5	2.5	1.0	4
NE clump	0.35	1.75	0.7	0.2

fainter than $M_I \approx -21$. This also can be seen by visual inspection of the central regions of the two clumps.

Although this statistical method provides a relative measure of the LFs of the two clumps, it is less secure than using redshift based LFs. A possible explanation of the differing LFs of the two clumps might be that a distant cluster lies behind the SW clump. Figure 12 shows the distribution of redshifts centered on the SW peak and although two weak peaks occur near $cz = 53000$ and 80000 km s^{-1} there is no significant structure for $cz < 120000 \text{ km s}^{-1}$.

Were a substantial number of redshifts available for i' fainter than 20, this possibility could possibly be sorted out.

Nevertheless, a distant cluster might show detectable differences in centre and in shape compared to the foreground cluster. To look for these effects, the galaxy sample was divided into bright ($M_I < -20.0$), and faint ($-16.0 > M_I \geq -20.0$) galaxies. Their values of L_I were converted from i' as described above and isophotes were constructed using the Silverman (1986) adaptive kernel smoothing method. Figure 13 has bright galaxies on the left. Both clumps show roughly circular isophotes and the peak of the SW clump is the higher. The isophotes for the faint galaxies on the right differ. Here the NE clump is diminished relative to the SW clump, which is stronger. Using the faint galaxies,

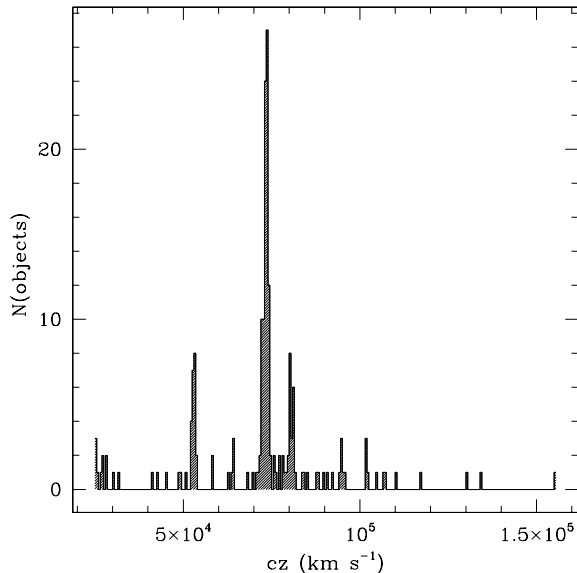


Figure 12. Redshifts of all galaxies centred on the SW clump. The strong peak near $z = 0.245$ comes from the Abell 2465 galaxies.

the peak of the SW clump is only slightly farther away from that of the NE clump along the axis joining them by ≈ 0.02 or 0.3 Mpc.

The red sequence provides a second test for a distant cluster behind the SW clump. Such a cluster might have a typical I -band Schechter function ($\alpha = -1.27$, $M^* = -21.66$; e.g., Harsano & De Propis 2009). Assuming that the SW clump's LF is the same as that of NE plus the Schechter function, the distance modulus of the distant cluster should be larger by $\Delta DM \approx 3.2$ mag., or its distance modulus is 43.6, and $z \approx 0.85$. Although such a cluster lies beyond the currently available spectroscopy, at this z the change in K -corrections alone would make the distant cluster's $(r' - i')$ colour redder by about 1.3 mag. (e.g., Fukugita et al. 1995). This effect is well illustrated by Gilbank et al. (2008) for composite clusters in $(R - z')$ for $z = 0.4$ to 0.9 which include evolutionary effects. This shifting of the red sequence could distort the shape of the red sequence of the SW region relative to the NE. One complication is that at increasing z , the blue sequence grows stronger and by $z = 0.85$ it lies near the low redshift red sequence. However, the red sequence remains the stronger and should still be detectable.

To look for the shifted red sequence of a distant cluster, galaxies with $20.0 \leq i' \leq 24.4$ were binned in $(r' - i')$ for both clumps within 2.75 of their centres. As shown in Figure 14, there is no apparent enhancement in $(r' - i')$ near 1.7 for the SW region compared to the NE. Applying the two-sample Kolmogorov-Smirnov test (Press et al. 1992) supports the null hypothesis that the two samples are the same at the 99.8% level so a substantial cluster directly behind the SW clump seems unlikely. In the future, bluer colours would provide a more sensitive test.

In a test to fit different luminosity functions to each clump, two approaches were employed. The first uses the prescription of Bingelli, Sandage, & Tammann (1988), also similar to Wilson et al. (1997). The E, S0, and spiral con-

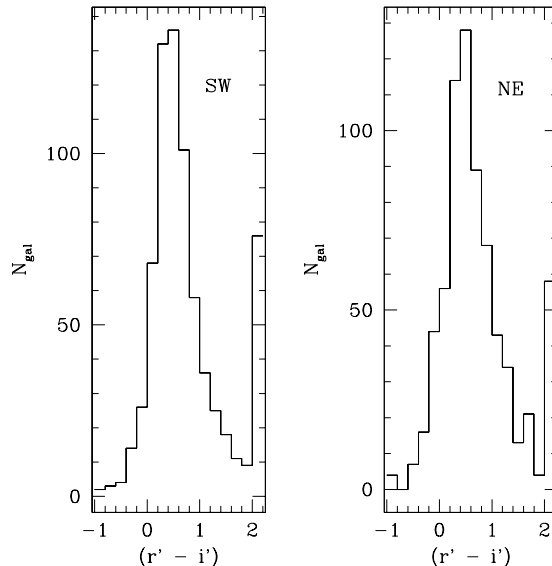


Figure 14. Histograms of the colour distributions for galaxies within 2.75 in the two clumps of Abell 2465 with apparent magnitudes $20.0 \leq i' \leq 24.4$.

stituents are fit by Gaussian functions and the dEs and dIrr follow Schechter functions. Here the fitting values of Jerjen & Tammann (1997) are used for the Gaussians and Bingelli et al. (1988) for the Schechter functions. The B -band magnitude zero-points were adjusted using mean $(B - I)$ colours for each galaxy type from Fukugita et al. (1995) and Smail et al. (1998) for the dEs. In Figure 15 reasonable fits to the observed luminosity functions of the two clumps are achieved. The relative proportions of the galaxy types given in Table 5 are similar for the two clumps, whilst the relative number of dEs is approximately five times higher in the SW clump compared to the NE. It should be noted that $\alpha = -1.35$ for the dE Schechter function is employed rather than the steeper $\alpha \approx -1.6$ to -2 predicted by Λ CDM.

The second approach uses the double Schechter function Popesso et al. (2006) and others found that fits many clusters. Using published parameter values, these LFs do not agree well with those of Abell 2465. Other authors, e.g., Wolf et al. (2003) and Christlein et al. (2009) also find that simple luminosity functions do not fit available data and obtain luminosity functions similar in shape found here. They interpret the luminosity functions as the sum of early types plus a rising late-type component composed of mostly faint blue star-forming galaxies.

Independantly of the fitting method, the outstanding feature is the difference in the numbers of faint galaxies following the dE Schechter function. There is an excess in the SW clump which is the more luminous and slightly less massive, while the NE clump has fewer faint galaxies. Additional spectroscopic data are needed to establish the nature of the faint galaxies in the SW clump.

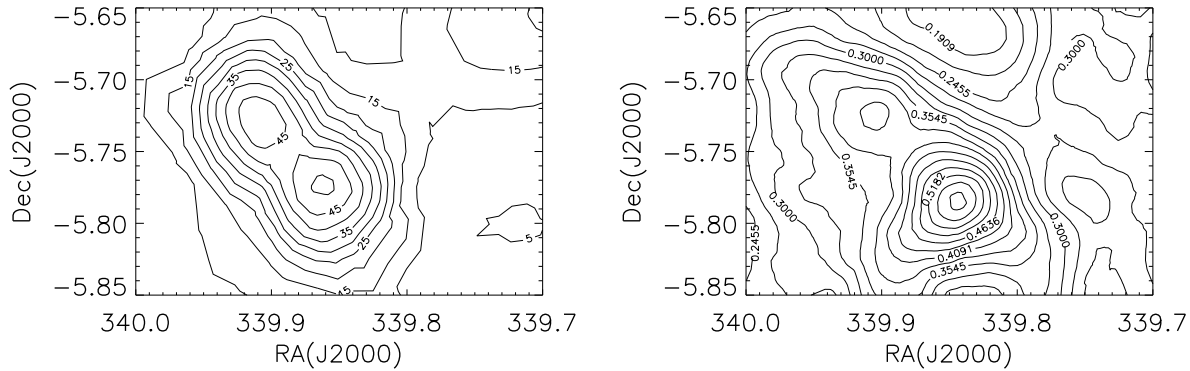


Figure 13. *I*-band isophotes for galaxies in the field of Abell 2465 constructed with the adaptive kernel method. (Left) All galaxies on the red sequence shown in Figure 3 brighter than $M_I = -20.0$. (Right) All the fainter galaxies with $-16.0 > M_I \geq -20.0$. The dominance of the SW clump compared with the NE is notable. The scale of the isophotes is in arbitrary units.

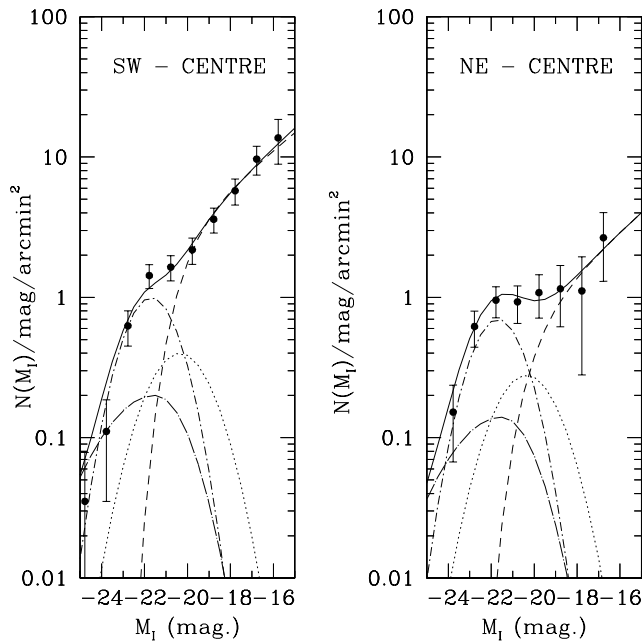


Figure 15. Fits to the luminosity functions in Figure 11 using the prescription given in Table 5. long dash - dot ellipticals, short dash - dot S0s, dots spirals, and short dashes dEs. The solid curve is the sum of the individual components.

5 LIGHT PROFILES OF THE CLUMPS

The luminosity functions data are also employed to construct the light profiles. The apparent i' magnitudes were converted to absolute M_I Cousins magnitudes using the transformation in §4.2. The total light, L_p , within circular apertures of radius R_p was measured starting from the cluster centres increasing the radius in $0'.15$ steps for projected radii. For $R_p \leq 2'.75$ circular areas were taken but for larger radii, the areas were corrected for the area of the missing segment that overlaps the other clump. The sums inside the aperture radii, or growth curves give smoother curves than the projected luminosity.

The choice of the cluster centre affects results near the origin, but its influence decreases with radius. The BCGs and the X-ray centres of the NE clump differ by $\sim 22''$. Therefore the aperture profiles were constructed several times taking different centres within $\pm 22''$ and averaged. This affects the central few points, but becomes negligible for radii larger than $\sim 0'.45$, where the background's uncertainty dominates. The errors are estimated from the variance of the different counts and the counting statistics. The resulting curves are shown in Figure 16 where they are compared with NFW growth curves for different concentration indices.

Several profile functions are known to fit galaxy clusters (e.g., Katgert et al. 2004). Although the purpose here is not to determine the optimal profile function, it is convenient to compare NFW profiles (Navarro, Frenk & White 1997) to the data in Figure 16. The curves, assuming that $M/L \approx \text{const.}$, are for different concentration parameters, c , computed using the formula for the projected mass,

$$M_p(R) = g(c)M_v \left[\frac{C^{-1}[1/(c\tilde{R})]}{|c^2\tilde{R}^2 - 1|^{1/2}} + \ln\left(\frac{c\tilde{R}}{2}\right) \right], \quad (8)$$

(Lokas & Mamon 2001), where $\tilde{R} = R/r_v$, M_v is the virial mass,

$$g(c) = \frac{1}{\ln(1+c) - c/(1+c)}, \quad (9)$$

and $C^{-1}(x) = \cos^{-1}(x)$ for $R > r_s$ and $\cosh^{-1}(x)$ if $R < r_s$. The best fitting NFW profile was found using the Kolmogoroff-Smirnov test (Kreyszig 1991; Press et al. 1992) on the projected growth curve in Figure 16. Note that data are displayed in a semi-log plot whilst the KS test is done linearly. In these determinations, the spectroscopic values of r_{200} were used. SW follows curves with $c = 4 \pm 2$ and NE lies closer to $c = 10 \pm 5$. However, although the single NFW profile fits the NE region relatively well, agreement is poorer for the SW clump, particularly near $R_p/r_{200} \approx 0.3$ where the data rise compared to the nearby smooth NFW curves for different values of c .

Viewing Figure 1, this rise should result from the bright BCG complex near the centre of the SW clump. Consequently, a more complicated composite profile containing a

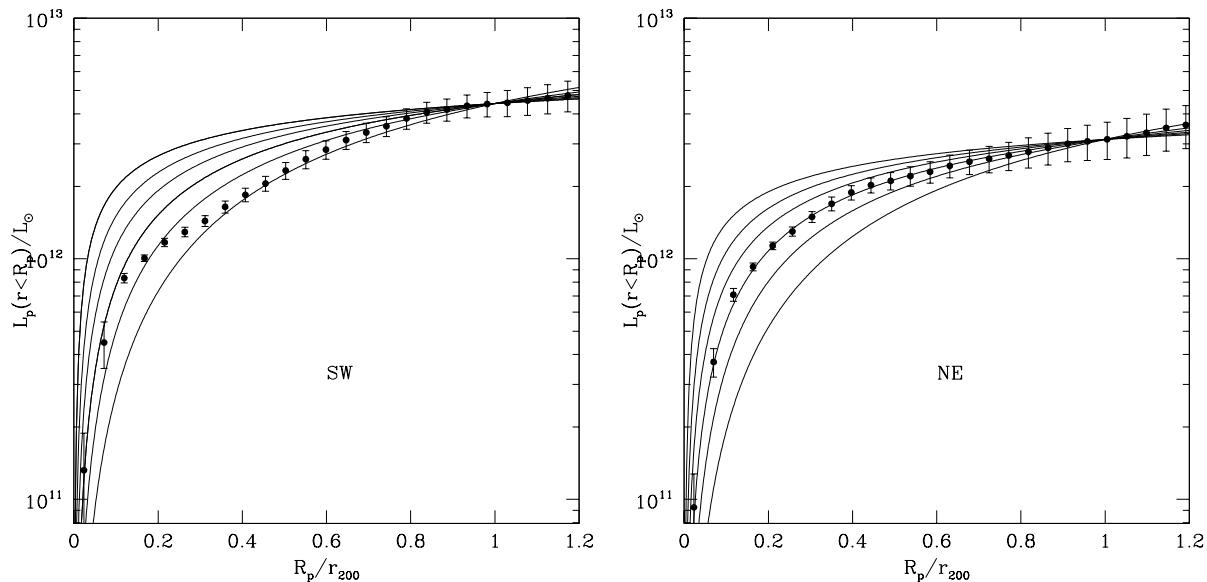


Figure 16. The total projected light inside radius R_p for the two clumps of Abell 2465 and their errors. Curves for NFW profiles with different concentration indices are superimposed; from top to bottom: $c = 100, 40, 20, 10, 5$, and 2 . SW has $L_p = 4.4 \times 10^{12} L_\odot$ at $r_{200} = 1.21$ Mpc and fits with $c \approx 4$, while NE has $L_p = 3.8 \times 10^{12} L_\odot$ at $r_{200} = 1.25$ Mpc with $c \approx 10$.

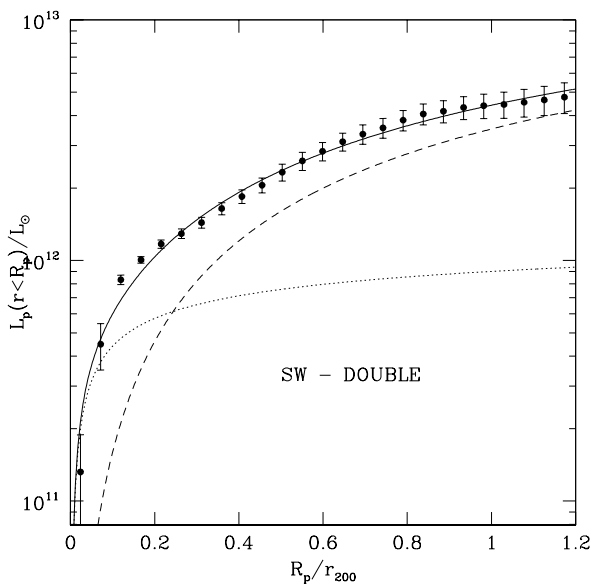


Figure 17. Fit to the growth curve of the SW clump of Abell 2465 data given in Figure 16 using the double model discussed in the text. The dashed curve is for a NFW profile with $c = 1.0$ and the dotted curve is for $c = 120$. The solid curve is their sum.

bright core yields a better fit. However, which combination of profiles is the best is difficult to decide with the present data. One possibility shown in Figure 17 is to add two NFW profiles, one with $c = 120$ which gives a sharp core and the other with $c = 1.0$ which produces an extended outer region. This confirms that the SW clump is more centrally concentrated as it also is in X-rays.

Measurements of c based on mass give somewhat different values for c . Katgert et al. (2004) find $c = 4_{-1.5}^{+2.7}$ from a

cluster ensemble, while Biviano & Girardi (2003) find $c \approx 5.6$ and Carlberg et al. (1996) obtain $c \approx 4$. Thus c for the SW component might lie within the normal range except for its core, but for NE clump c is larger. Theoretical values of c based on the buildup of dark haloes in CDM models (e.g., Zhao et al. 2003) agree with the lower value of c , so the higher value for NE is difficult to explain, although the value of c depends on the accretion rate of the cluster.

The value of c does depend on the choice of r_{200} . However, to achieve a fit resulting in $c = 5$ for the NE clump requires lowering r_{200} to half its spectroscopic value, or 6σ . If the mass distributions in the subclusters of Abell 2465 differ from those found here for light, this may imply that they may have been disturbed by the merging process.

As seen in Figure 16, the total luminosities are $L_I = 4.4 \pm 0.6 \times 10^{12} L_\odot$ for SW and $L_I = 3.8 \pm 0.7 \times 10^{12} L_\odot$ for NE. Using the mean of the virial and X-ray masses, gives mass-to-light ratios in the I -band of $M/L = 84 \pm 12$ and $M/L = 112 \pm 20$ respectively. Noting that $(R - I) \approx 0.7$ for early-type galaxies, in the R -band (Fukugita et al. 1995), $\Upsilon_R \approx 1.9\Upsilon_I$ so the mass ratios lie marginally within the range for single galaxy clusters which is $\Upsilon_R = 200 \pm 50$ in the R -band (Binney & Tremaine 2008). The more massive NE clump has the higher M/L while the SW clump has the more concentrated core.

6 DISCUSSION

The mass ratio near unity indicates that the components of Abell 2465 are undergoing a major merger. However, the question that needs to be answered is whether Abell 2465 is beginning the merger or if a collision has already occurred. The main properties of this double galaxy cluster have both some normal and some unusual properties. On one hand, the masses and virial radii are similar to single clusters as are

their velocity dispersion anisotropies. On the other hand, the differences in their luminosity functions, M/L , and the presence of many star-forming galaxies located between the two clumps offer additional clues to the processes involved in their earlier interaction which tend to favour the past collision hypothesis.

6.1 Separation of the Baryonic and Collisionless Components

After pericentric passage in galaxy cluster collisions, a generic result is that the highly heated baryonic gas is temporarily retarded relative to the collisionless dark matter and galaxies with the result that the X-ray centres are closer together than the dark matter centres. The separation is expected to be smaller for nearly equal mass clusters than it is for higher mass ratios (e.g., Poole et al. 2006; Tormen et al. 2004). The gas cools and re-merges with the collisionless components at later times. These effects are observed in several recent ($\tau_{\text{coll}} \lesssim 0.1 - 0.3$ Gyr) collisions with higher mass ratios, notably 1E0657-56 (Clowe et al. 2006), Abell 2146 (Russell et al. 2010), and MACS J0025.4-1222 (Bradač et al. 2008b), where X-ray emission is between the dark matter clumps as revealed by lensing and the galaxies.

For Abell 2465, the X-ray and BCG centres are in Table 1. Displacements occur along the axis in Figure 9 joining the two clumps, putting the X-ray peaks between the BCGs. These amount to $22''.1$ (85 kpc) for the NE and $2''.4$ (9 kpc) for the SW. The isophotal peaks from the galaxies in Figure 13 are more unreliable. These change by $\sim \pm 25''$ depending on whether different magnitude ranges or galaxy numbers are used to construct the contours. These place the centres of the galaxy distributions near or slightly inside the X-ray peaks along the axis. Relative to the $5''.5$ separating the clumps, displacements are small compared to the colliding clusters above. Thus, while the separation of the components is consistent with a past collision, using the X-ray and BCG locations, their small separations suggest that the NE and SW subclusters have not recently collided.

6.2 Nature of the Interaction

The radial infall model (Beers, Geller, & Huchra 1982) has often been used as a first approximation to study head-on collisions, despite its obvious limitations, including neglect of dynamical friction and gas dynamics. It is an analytic solution based on the Einstein-de Sitter cosmological model and has been employed by many investigators (e.g., Gregory & Thompson 1984; Beers et al. 1991; Scodreggio et al. 1995; Colless & Dunn 1996; Mohr & Wegner 1997; Donnelly et al. 2001; Yuan et al. 2005; Hwang & Lee 2009) and will only be outlined here. Briefly, two mass points with total mass, M , following radial orbits are assumed and R , their separation, V , the relative velocity, and the time, t are given parametrically in terms of the development angle, η . The masses coincide at pericentre when $\eta = 0, 2\pi, \dots$ and are at apocentre when $\eta = \pi, 3\pi, \dots$. The solution requires M , the projected distance, R_p , and t_0 , the system's age, usually set equal to the age of the Universe. Since the inclination angle φ , is unknown, the system of equations can be written in terms of $R_p = R \cos \varphi$, the projected distance between the

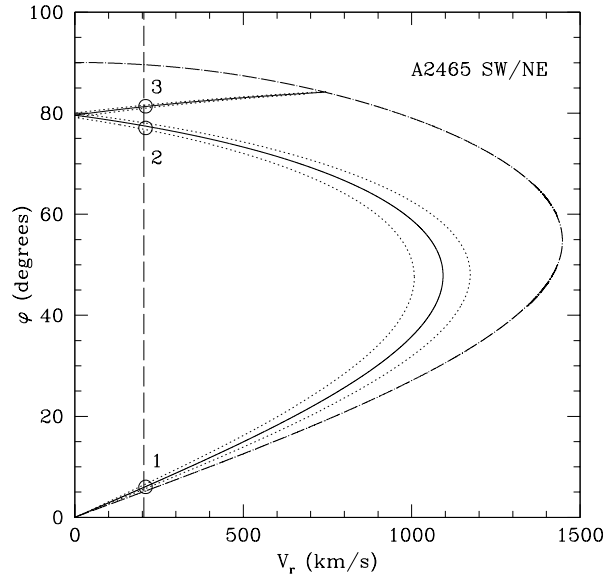


Figure 18. Radial infall model solutions for Abell 2465. Right-most (dot-dash) curve is limit of bound solutions; solutions to its right are unbound. Solutions for $8 \times 10^{14} M_\odot$ (solid) and $7 \times 10^{14} M_\odot$ (dotted) lie on either side. The vertical dashed line shows the measured value of V_r and circles mark the three possible solutions indicated by the numbers.

masses, radial velocity difference, $V_r = V \sin \varphi$ and M . The bound case for the two masses obeys $V_r^2 \leq 2GM \sin^2 \varphi \cos \varphi$ and three solutions are possible: two collapsing or ingoing and one expanding or outgoing. The M and V_r of §3 place the cluster pair within the bound region and hence the unbound case is not considered.

Using $M = 8 \pm 1 \times 10^{14} M_\odot$, $R_p = 1.265$ Mpc, and 10.895 Gyr, the age of the universe at $z = 0.245$, one can construct curves of the solutions within the permitted regions shown in Figure 18.

With $V_r = 205 \text{ km s}^{-1}$, the three possible solutions are: (1) $\eta = 5.17$ radians, $\varphi = 5.95$, $R = 1.31$ Mpc, $R_m = 4.53$ Mpc, and $V = -1978 \text{ km s}^{-1}$. (2) $\eta = 3.53$ radians, $\varphi = 77.5$, $R = 6.01$ Mpc, $R_m = 6.07$ Mpc, and $V = -210 \text{ km s}^{-1}$. (3) $\eta = 2.68$ radians, $\varphi = 81.3$, $R = 8.59$ Mpc, $R_m = 8.81$ Mpc, and $V = +208 \text{ km s}^{-1}$. Intuition suggests that either solution (2) or (3) might be preferable given the low observed value for V_r , placing the two clumps near apocentre, but further data are required.

Numerical simulations provide a better time scale estimate of galaxy clusters, including galaxies, baryonic and dark matter. The colliding models typified by e.g., Roettiger et al. (1996; 1997), Ritchie & Thomas (2002), Poole et al. (2006; 2008), etc while idealized and differing in details, predict similar effects in the collisions and suggest shorter times between collisions than the radial infall model predicts.

Published merger models focus on X-ray data and employ several simplifications, including e.g., assumed initial density profiles, velocities, and spherical symmetry. Nevertheless, three effects common to the models are important for this study. (1) Head-on and off-centre simulations generally merge soon after their second crossing, indicating that

the two subclusters in Abell 2465 have collided at most once or are merging for the first time. (2) The gas components' temperatures spike when the two centres cross and cool rapidly. Following Ritchie & Thomas (2002), the collision of $M = 4 \times 10^{14} M_{\odot}$ equal masses, close to that estimated for Abell 2465, the gas temperature reaches ~ 10 keV and cools to ~ 3 keV in about 3 to 4 Gyr as the clumps separate to apocentre and begin reconverging. The temperatures of §3.3, are consistent with this time scale if the cluster is in the post-impact stage, but cannot be used to prove the physical state of the merger. (3) The collision produces an expanding impact disk of gas as two clusters pass through each other which breaks into two sections continuing outward with the main masses. Zu Hone, Lamb, & Ricker (2009) have discussed ring formation. The dark matter components pass through each other and the core regions are not disrupted.

Tormen et al. (2004) analysed the evolution of merging galaxy cluster satellites from hydrodynamical N-body simulations including dark matter and baryonic gas. They fitted the statistics of collisions including orbital properties, velocity dispersions, gas temperatures, etc. as a function of the satellite and main cluster pre-merger mass ratio, m_v/M_v . For $m_v/M_v \approx 0.9$, ~ 2 Gyr is required to reach apocentre. Consequently, this and the temperature aging indicate that the time since the collision is of order $\tau \sim 2-4$ Gyr.

The cluster light profiles and luminosity functions provide additional clues to the interaction of the two components of Abell 2465. The SW clump has a sharper core in both the visual and X-rays as well as more faint galaxies shown in Figures 11 and 13. The two well studied cluster collisions involving recent impacts, 1E0657-56 and Abell 2146 (Clowe et al. 2006; Russell et al. 2010), have lower mass ratios of $m_v/M_v \approx 0.1$ and 0.3 respectively. Both exhibit a relatively dense 'bullet' emerging from a more extended 'target,' and are near their pericentres, having collided $\tau \sim 0.1 - 0.3$ Gyr ago, compared to $\tau \sim 3$ Gyr for the cooler Abell 2465 now near apocentre. By analogy with these two objects, one identifies the SW clump with its sharper optical and X-ray core as the bullet and the more extended NE clump as the target. The presence of the 1.4 GHz radio source and its higher mass further imply that the NE clump is the primary.

Although cluster cores are not disrupted, the outer regions can be modified. The published simulations show complex behavior of the collisionless component. Bekki (1999) and Roettiger, Burns, & Loken (1993) demonstrate that the distribution of dark matter in the secondary expands after the collision. Using the simple impact approximation (Binney & Tremaine 2008), energy changes accompanied by mass loss of the impacting systems occur. Intuitively one expects core regions to contract as they meet while the outer layers of the clusters expand (e.g., Aguilar & White 1985; Funato & Makino 1999). Some of the off-centre models (e.g., Poole et al. 2006; Ricker & Sarazin 2001) show that when the secondary core reaches apocentre and turns around, there can be a significant displacement of the cluster's outer region which is assisted by a gravitational slingshot similar to a trailing tidal trail. Thus the SW clump might be expected to be surrounded by more debris than the NE which accounts for its excess of faint galaxies.

6.3 On the star forming components

Previous investigations have found inconclusive results for different cluster pairs regarding star formation. Hwang & Lee (2009) found enhanced star formation activity between the subclusters of Abell 168 which they concluded had passed through each other and none in Abell 1750 which may be in an early stage of merging. Rawle et al. (2010) have found significant star formation in the bullet cluster using Herschel. Caldwell & Rose (1997) reported enhanced star forming in interacting clusters as did Cortese et al. (2004) for Abell 1367, Ferrari et al. (2005) for Abell 3921, and Johnston-Hollitt et al. (2008) for Abell 3125/28, but Tomita et al. (1996) and De Propis et al. (2004) found no correlation for blue galaxies and mergers. Ma et al. (2010) have described MACSJ0025.4-1225, which has several features in common with Abell 2465, as a post-major-merger. They find enhanced numbers of starforming galaxies which they interpret to have been produced by the merger. The emission line galaxies in Abell 2465, however, lends weight to the hypothesis that cluster mergers enhance star formation.

It has always been difficult to pin down the process or combination of processes leading to star formation in galaxies. Bekki (1999) found that the time-dependent tidal gravitational field is an important effect that can trigger starburst galaxies in mergers. Martig & Bournaud (2008) also find that tidal fields in merging dense cosmological structures and the outskirts of galaxy clusters can induce star formation. The presence of apparently distorted star forming galaxies with no detected companions in the clusters could be consistent with this mechanism.

7 CONCLUSIONS

Spectroscopic and photometric observations of the double galaxy cluster Abell 2465 are presented. There are five main conclusions that can be drawn.

1. Concerning the cluster dynamics, the virial masses of the two subclusters are found from fuzzy clustering, which is used to estimate the probability of a galaxy's membership in each clump, with the result that $M_v = 4.0 \pm 0.8 \times 10^{14} M_{\odot}$ for the NE member and $M_v = 3.8 \pm 0.8 \times 10^{14} M_{\odot}$ for the SW member and the virial radii are $r_{200} = 1.21 \pm 0.11$ Mpc and 1.24 ± 0.09 Mpc for NE and SW respectively. The masses compare well with those from X-ray scaling relations that also give temperatures of 4.1 ± 0.3 and 3.75 ± 0.2 keV respectively. The velocity difference between the two subclusters is found to be $\Delta V = 205 \pm 149$ km s $^{-1}$ which confirms that they are related. Measurement of the clusters' velocity dispersions with radius assuming spherical symmetry indicate that the anisotropy parameter, β , is low.

2. There is an excess of star forming galaxies showing emission lines. Of cluster members observed spectroscopically in Figure 8, 37% have detectable H α emission. These have the properties of star forming galaxies. There are more emission line objects in the SW clump than in the NE clump and there appears to be more emission line galaxies than non-emission between the two clumps. This does not seem to be explained by a selection bias. There is no evidence for strong AGN activity in Abell 2465. This number of emission line objects between the clump centres is unusual when compared to single galaxy clusters.

3. The r' and i' magnitudes show well defined red sequences in each subcluster. The luminosity functions determined within the central 0.6 Mpc of each clump indicate a normal mixture of galactic types. However, the SW region has more galaxies fainter than $M_I = -20.0$ than its NE companion. This could result from their collision or otherwise would suggest different formation histories. The possibility of a background cluster needs to be further checked.

4. The light profiles of both components measured as growth curves were fitted using NFW profiles. The NE clump is fit with a somewhat high concentration parameter $c = 10$, although this depends on the adopted virial radius. The SW clump is fit rather badly with $c \sim 4$ and needs a profile with a more compact core. A better fit is a sharp core ($c = 120$) surrounded by an extended outer region ($c = 1.0$). This is consistent with Figure 6 and published ROSAT data showing that the X-ray core radii differ with r_c of NE being about three times larger than that of the SW and indicates that SW has a cooling core. The derived I -band mass to light ratios are $\Upsilon_I = 84 \pm 12$ and 112 ± 20 which puts them in the normal range for galaxy clusters.

5. A consistent picture of the collision of the Abell 2465 components is discussed. It is possible that the pair collided 2-4 Gyr ago and are now near maximum separation. The small displacements of the dark matter and baryonic matter as judged by the X-ray data and distribution of the galaxies is consistent with their re-merging after the collision. The high percentage of emission line galaxies in the spectroscopic sample may be a consequence of the collision and are the strongest argument for a past interaction, but this might also be the case if the merger is just starting and interaction occurs along the interface between the two clusters. More models that include the dynamics of the galaxies would be helpful.

A weak lensing study of the two components of Abell 2465 is under way.

ACKNOWLEDGEMENTS

Many of the galaxy spectra were obtained through the Service Observing Programme of Anglo-Australian Observatory and I wish to express my gratitude. The imaging observations used in this paper were based on observations obtained with MegaPrime/MegaCam, a joint project of CFHT and CEA/DAPNIA, at the Canada-France-Hawaii Telescope (CFHT) which is operated by the National Research Council (NRC) of Canada, the Institut National des Sciences de l'Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii. This work is based in part on data products produced at TERAPIX and the Canadian Astronomy Data Centre as part of the Canada-France-Hawaii Telescope Legacy Survey, a collaborative project of NRC and CNRS. I thank the Canadian TAC for granting the time and the QSO team for obtaining the imaging data. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Many thanks to Dr. J. J. Mohr and Mr. Dane Owen for help on the MDM pho-

tometry, Mr. R. E. Johnson for discussions, and Dr. Heinz Andernach for comments.

REFERENCES

- Aguilar L., White S. D. M. 1985, *ApJ*, 295, 374
 Anderberg M. R. 1973, *Cluster Analysis for Applications*, Academic Press, New York
 Angus, G. W., McGaugh S. S. 2008, *MNRAS*, 383, 417
 Angus G. W., Famaey B., Diaferio A. 2010, *MNRAS*, 402, 395
 Bagchi J. et al. 2006, *Science*, 314, 791
 Balogh M. et al. 2004, *MNRAS*, 348, 1355
 Bekki K. 1999, *ApJ*, 510, L15
 Beers T. C., Gebhardt K., Forman W., Huchra J. P., Jones C. 1991, *AJ*, 102, 1581
 Beers T. C., Geller M. J., Huchra J. P. 1982, *ApJ*, 257, 23
 Bertin E. 2009, *SExtractor v2.5 User's manual*, <http://astroa.physics.metu.edu.tr/MANUALS/sextractor>
 Bertin E., Arnouts S. 1996, *A&AS*, 117, 393
 Bingelli B., Sandage A., Tammann G. A. 1988, *ARA&A*, 26, 509
 Binney J., Merrifield M. 1998, *Galactic Astronomy*, Princeton Univ. Press, Princeton, p. 53
 Binney J., Tremaine S., 2008, *Galactic Dynamics*, Princeton Univ. Press, p. 655
 Biviano A., Girardi M. 2003, *ApJ*, 585, 205
 Blanton M. R. et al. 2003, *ApJ*, 592, 819
 Blanton M. R., Roweis S. 2007, *AJ*, 133, 734
 Bonafede A., Giovannini G., Feretti L., Govoni F., Murgia M. 2009, *A&A*, 494, 429
 Bradač M. et al. 2008a, *ApJ*, 681, 187
 Bradač M., Allen S. W., Treu T., Ebeling, H., Massey R., Morris R. G., von der Linden A., Applegate D. 2008b, *ApJ*, 687, 959
 Brownstein J. R., Moffat J. W. 2007, *MNRAS*, 382, 29
 Caldwell N., Rose J. A. 1997, *AJ*, 113, 492
 Cappellari M. et al. 2006, *MNRAS*, 366, 1126
 Carlberg R. G., Yee H. K. C., Ellingson E., Abraham R., Gravel P., Morris S., Pritchet C. J. 1996, *ApJ*, 462, 32
 Chen, Y., Reiprich T. H., Böhringer H., Ikebe Y., Zhang Y.-Y. 2007, *A&A*, 466, 805
 Chionis T. S., Gaskell C. M. 2008, *AJ*, 135, 264
 Clowe D., Bradač M., Gpnzales A. H., Markevitch M., Randall S. W., Jones C., Zaritsky D. 2006, *ApJ*, 648, 109
 Christlein D., Zabludoff A. I. 2003, *ApJ*, 591, 764
 Christlein D., Gawiser E., Marchesini D., Padilla N. 2009, *MNRAS*, 400, 429
 Chung S. M. 2010, *BAAS*, 42, 601
 Colless M., Dunn A. M. 1996, *ApJ*, 458, 435
 Condon J. J., Cotton E. W., Griesen E. W., Yin Q. F., Perley R. A., Taylor G. B., Broderick J. J. 1998, *AJ*, 115, 1693
 Cortese L., Gavazzi G., Boselli A., Iglesias-Paramo J, Carrasco L. 2004, *A&A*, 425, 429
 De Lorenci V. A., Faundez-Abans M., Pereira J. P. 2009, *A&A*, 503, 1
 De Propis R. et al. 2004, *MNRAS*, 351, 125
 Diaferio A. 1999, *MNRAS*, 309, 610
 Dickey J. M., Lockman F. J. 1990, *ARA&A*, 28, 215
 Donnelly R. H., Forman W., Jones C., Quintana H., Ramirez A., Churazov E., Gilfanov M. 2001, *ApJ*, 562, 254
 Dressler A., Schechtman S. A. 1988, *ApJ*, 95, 985
 Farrar G.R., Rosen R. A. 2006, *PhRvL*, 98, 1302
 Fasano G., Franceschini A., 1987, *MNRAS*, 225, 155
 Ferrari C., Maurogordato S., Cappi A., Benoist C. 2003, *A&A*, 399, 813
 Ferrari C., Benoist C., Maurogordato S., Cappi, A., Slezak E. 2005, *A&A*, 430, 19
 Feretti L. 2002, *IAU Symp*, 199, 133
 Fukugita M., Shimasaku K., Ichikawa T. 1995, *PASP*, 107, 945

- Funato Y., Makino J. 1999, *ApJ*, 511, 625
- Gan G., Ma C., Wu J. 2007, *Data Clustering, Theory, Algorithms, and Applications*, SIAM, Philadelphia
- Geller M. J., Beers T. C. 1982, *PASP*, 94, 421
- Gilbank D. G., Yee H. K. C., Ellingson E., Gladders M. D., Loh, Y.-S., Barrientos, L. F., Barkhouse, W. A. 2008, *ApJ*, 673, 742
- Girardi M., Barrena R., Bosch W., Ellingson E. 2008, *A&A*, 491, 379
- Girardi M., Giuricin G., Mardirossian F., Mezzetti M., Bosch W. 1998, *ApJ*, 505, 74
- Goto T. et al. 2005, *ApJ*, 621, 188
- Gregory S. A., Thompson L. A. 1984, *ApJ*, 286, 422
- Haines C. P., Smith G. P., Egami E., Okabe N., Takada M., Moran S. M., Umetsu K., 2009, *MNRAS*, 396, 1297
- Hallman E. J., Markevitch M. 2004, *ApJ*, 610, L81
- Hansen S. H., Piffaretti R. 2007, *A&A*, 476, L37
- Harsano D., De Propis R. 2009, *AN*, 330 937
- Hayashi E., White S. D. M. 2006, *MNRAS*, 370, L38
- Heiderman A. et al. 2009, *ApJ*, 705, 1433
- Heisler J., Tremaine S., Bahcall J. N. 1985, *ApJ*, 298, 8
- Holwerda B. W. 2005, *Source Extractor for Dummies*, astro-ph/0512139
- Höppner F., Klawonn F., Kruse R., Runkler T. 1999, *Fuzzy Cluster Analysis: Methods for Classification, Data Analysis, and Image Recognition*, John Wiley & Sons, Chichester
- Host O. 2009, *Nucl Phys. B*, 194, 111
- Host O., Hansen S. H., Piffaretti R., Morandi A., Ettori S., Kay S. T., Valdarnini R. 2009, *ApJ*, 690, 358
- Hwang H. S., Lee M. G. 2009, *MNRAS*, 397, 2111
- Jee M. J. et al. 2007, *ApJ*, 661, 728
- Jerjen H., Tammann G. A. 1997, *A&A*, 321, 713
- Johnston-Hollitt M., Sato M., Gill J. A., Fleenor M. C., Brick A.-M., 2008, *MNRAS*, 390, 289
- Jordi K., Grebel E. K., Ammon K. 2006, *A&A*, 430, 339
- Kalberla P. M., Burton W. B., Hartmann Dap, Arnal, E. M., Bajaja E., Morra, R., Pöppel W. G. L. 2005, *A&A*, 440, 775
- Katger P., Biviano A., Mazure A. 2004, *ApJ* 600, 657
- Kaufman L. & Rousseeuw P. J. 2005, *Finding Groups in Data*, John Wiley & Sons, Hoboken
- Kauffmann G., et al. 2003, *MNRAS*, 346, 1055
- Kewley L. J., Dopita M. A., Sutherland R. S., Heisler C. A., Trevena J. 2001, *ApJ*, 556, 121
- Kreyszig E. 1991, *Statistische Methoden und ihre Anwendungen*, 7. Auflage, Vandenhoeck & Ruprecht, Göttingen
- Kriessler J. R., Beers T. C. 1997, *AJ*, 113, 80
- Kubo J. M., Stebbins A., Annis J., Dell Antonio I. P., Lin H., Frieman J. A. 2007, *ApJ*, 671, 1466
- Landolt A. U. 2009, *AJ*, 137, 4186
- Leauthaud A. et al. 2007, *ApJS*, 172, 219
- Lokas E. L., Mamon G. A. 2001, *MNRAS*, 321, 155
- Ma C.-J., Ebeling H., Marshall P., Schrabback T. 2010, *MNRAS*, 406, 121
- McCracken H. J., Le Fevre O., Brodwin M., Foucaud S., Lilly S. J., Crampton D., Mellier Y. 2001, *A&A*, 376, 756
- Lopes R. H. C., Reid, I., Hobson P.R., 2007 in *Proceedings of "XI International Workshop on Advanced Computing and Analysis Techniques in Physics"*, PoS(ACAT)045
- Madgwick D. S. et al. 2002, *MNRAS*, 333, 133
- Markevitch M., Vikhlinin A. 2007, *PhysRep*, 443, 1
- Martig M., Bournaud F., 2008, *MNRAS*, 385, L38
- Mastropietro C., Burkner, A. 2008, *MNRAS*, 389, 967
- Maurogordato A. et al. 2008, *A&A*, 481, 593
- Merritt D., 1985, *AJ*, 90, 1027
- Miyamoto S., Ichihashi H., & Honda, K. 2008, *Algorithms for Fuzzy Clustering Methods in c-Means Clustering with Applications*, Springer-Verlag, Berlin
- Mohr J. J., Wegner G. 1997, *AJ*, 114, 25
- Natarajan P., Zhao H. 2008, *MNRAS*, 389, 250
- Navarro J. F., Frenk C. S., White S. D. M. 1997, *ApJ*, 490, 493
- O'Hara T. B., Mohr J. J., Bialek J. J., Evrard A. E. 2006, *ApJ*, 639, 64
- Okabe N., Umetsu K. 2008, *PASJ*, 60, 345
- Orrú E., Murgia M., Feretti L., Govoni F., Brunetti G., Giovannini G., Girardi M., Setti G. 2007, *A&A*, 467, 943
- Osipkov L. P., 1979, *PAZh*, 5, 77
- Penny S. J., Conslice C. J., De Rijcke S., Held E. V. Gallagher III, J. S., O'Connell R. W. 2010, *MNRAS*, 410, 1076
- Perlman E. S., Horner D. J., Jones L. r., Scharf C. A. Ebeling H., Wegner G., Malkan M. 2002, *ApJS*, 140, 265
- Pinkney J., Roettiger K., Burns J. O., Bird, C. M. 1996, *ApJS*, 104, 1
- Planelles S., Quilis V. 2009, *MNRAS*, 399, 410
- Pointecouteau E., Arnaud M., Pratt G. W. 2005, *A&A*, 435, 1
- Pointecouteau E., Silk J. 2005, *MNRAS*, 364, 654
- Poole G. B., Fardal M. A., Balbul A., McCarthy I. G., Quinn T., Wadsley J. 2006, *MNRAS*, 373 881
- Poole G. B., Babul A., McCarthy I. G., Sanderson A. J. R., Fardal M. A. 2008, *MNRAS*, 391, 1163
- Popesso P., Biviano A., Böhringer H., Romaniello M., Voges W. 2005, *A&A*, 433, 431
- Popesso P., Biviano A., Böhringer H., Romaniello M. 2006, *A&A*, 445, 29
- Press W. H., Teukolsky S. A., Vetterling W. T., Flannery B. P. 1992, *Numerical Recipes in Fortran*, 2nd ed., Cambridge: Univ. Press, Cambridge
- Ramella M., Biviano A., Pisani J., Bettoni D., Couch W. J., Onofrio M. D., Dressler A., Fasano G. Kjærgaard, P., Moles M., Pignatelli E., Poggiant, B. M. 2007, *A&A*, 470, 39
- Rawle T. D. et al. 2010, *A&A*, 518, 14
- Raymond J. C., Smith B. W. 1977, *ApJS*, 35 419
- Rines K., Geller M. J., Kurtz M. J., Diaferio A. 2005, *AJ* 130, 1482
- Reiprich T., Böhringer H. 2002, *ApJ*, 567, 740
- Ricker P.M. 1998, *ApJ*, 496, 670
- Ricker P. M., Sarazin C. L. 2001, *ApJ*, 561, 621
- Ritchie B. W., Thomas P. A. 2002, *MNRAS*, 329, 675
- Roettiger K., Loken C., Burns J. 1993, *ApJ*, 407, L53
- Roettiger K., Loken C., Burns J. O., 1996, *ApJ*, 473, 651
- Roettiger K., Loken C., Burns J. O., 1997, *ApJS*, 109, 307
- Russell H. R., Sanders J. R., Fabian A. C., Baum S. A., Donahue M., Edge A. C., McNamara B. R., O'Dea C. P. O. 2010, *MNRAS*, 406, 1721
- Rykoff E. S., Evrard A. E., McKay T. A., Becker M. R., Johnston D. E., Koester B. P., Nord B., Rozo E., Sheldon E. S., Stanek R., Wechsler R. H. 2008, *MNRAS*, 387, 28
- Salvador-Solé E., Sanromà M. González-Casado, G. 1993, *ApJ*, 402, 398
- Sanderson, A. J. R., Ponman, T. J., Finoguenov, A., Lloyd-Davies, E. J. 2003, *MNRAS*, 340, 989
- Sakellou I. Ponman T. J. 2004, *MNRAS*, 351, 1439
- Sarazin C. L. 1986, *RvMP*, 58, 1
- Sato M., Sato Y., Jain L. C. 1997, *Fuzzy Clustering Models and Applications*, Physica-Verlag, Heidelberg
- Schechter P. 1976, *ApJ*, 203, 297
- Schmidt F., Vikhlinin A., Hu W. 2009, *PhysRevD*, 80, 083505-1
- Scodeggio M., Solanes J. M., Giovanelli R., Haynes M. P. 1995, *ApJ*, 444, 41
- Serna A. 1996, *J. Comp. Phys.*, 129, 30
- Shan H. Y., Qin B., Fort B., Tao C., Wu X.-P. 2010, *MNRAS*, 406, 1134
- Silverman B. W. 1986, *Density Estimation for Statistics and Data Analysis*, Chapman and Hall, London
- Sakellou I., Ponman T. J. 2004, *MNRAS*, 351, 1439
- Skilman S. W., Hallman E. J., O'Shea B. W., Burns J. O., Smith B. D., Turk M. J. 2010, *arXiv:1006.3559v1*

- Slee O. B., Roy A. L., Murgia M., Andernach H., Ehle M. 2001, AJ, 122, 1172
- Smail I., Edge A. C., Ellis R. S., Blandford R. D. 1998, MNRAS, 283 124
- Springel V., Farrar G. R. 2007, MNRAS, 380, 911
- Tanaka N., Furuzawa A., Miyoshi J., Tamura T., Takata T. 2010, PASJ, 62, 743
- Takizawa M. 2000, ApJ, 532, 183
- Takizawa M., Nagino R., Matsushita K. 2010, PASJ, 62, 951
- Thomas P. A. et al. 1998, MNRAS, 296, 1061
- Tomita A., Nakamura F. E., Takata T., Nakanishi K., Takeuchi T., Ohta K., Yamada T. 1996, AJ, 111, 42
- Tonry J., Davis M. 1979, AJ, 84 1511
- Tormen G., Moscardini L., Yoshida N. 2004, MNRAS, 350, 1397
- Tremaine S., Gunn J. E., 1979, PhRvL, 42, 407
- Tully R. B. 1980, ApJ, 237, 390
- van Weeren R. J., Intema H. T., Röttgering H. J. A., Clarke T. E. 2009, A&A, 508, 1269
- Vikhlinin A., McNamara B. R., Forman W., Jones C., Quintana H., Hornstrup A. 1998, ApJ, 502, 558
- Wegner G. Grogin N. A. 2008, AJ, 136, 1
- Wilms, J., Allen, A., McCray, R. 2000, ApJ, 542, 914
- Wilson G., Smail I., Ellis R. S., Couch W. J. 1997, MNRAS, 284, 915
- Wilson G. 2003, ApJ, 585, 191
- Wolf C., Meisenheimer K., Rix H.-W., Borch A., Dye S., Kleinheinerich, M. 2003, A&A, 401, 73
- Yan R., Newman J. A., Faber S. M., Konidakis N., Koo D., Davis, M. 2006, ApJ, 648, 281
- Yuan Q., Yan P., Ying Y., Zho, X. 2005, ChJAA, 5, 126
- Zhao D. H., Jing Y. P., Mo H. J., Börne, G. 2003, ApJ, 597, L9
- Zu Hone J. A., Lamb D. Q., Ricker P. M. 2009, ApJ, 696, 649
- Zu Hone J., Markevitch M. 2009, AIP Conf. Proc., 1201, Cluster Core Heating from Merging Subclusters, S. Heinz, E. Wilcots, eds., p. 383